DOCTOR OF PHILOSOPHY

Oculomotor and electrophysiological markers of cognitive distraction during low-level and complex visual tasks

Savage, Steven William

Award date:
2015

Oculomotor and electrophysiological markers of cognitive distraction during low-level and complex visual tasks

Steven William Savage

M.A. (Hons); MSc (Dist)

Doctor of Philosophy

University of Dundee
May 2015

Table of Contents

Acknowledgments

This thesis is dedicated to the memory of my late father Edwin Charles Savage who was with us at the beginning but could not witness the completion of this journey. Dad, you are and always will be my best friend and greatest teacher.

Mum, you have always been there for me. Your unwavering faith in me is what gives me the confidence to always seek greater challenges. You push me when I need pushing and comfort me when I need comforting. Thank you for everything!

My sincerest gratitude goes to Viola Marx for all of her assistance. Not only were you of invaluable practical help, but you were also there for me emotionally when I needed you to be. You have done more for me than I could ever put into words and I will always be grateful.

I would also like to thank both of my Supervisors, Dr. Ben Tatler and Dr Doug Potter. Without your patience and guidance such an ambitious project would not have been possible. I very much look forward to collaborating with you in the future.

To our school's technical Staff, especially John Morris and Fariad Umar for whom no task was to great or small, I truly appreciate your help and support throughout the years. My thanks also go to Dr Alissa Melinger and Dr Benjamin Vincent for helping to keep me on track by means of our biannual Thesis Monitoring Committee meetings.

All work and no play make Jack a dull boy so at this stage I would like to express my deepest gratitude to my friends who were there to distract me when I needed distracting. You are the reason I haven't (completely) lost my mind and I thank you for that.

Declaration of Originality

I, Steven William Savage, declare that I am the sole author of this thesis have consulted all references cited personally (unless otherwise stated). I have carried out the documented work myself under the supervision of Dr Benjamin W Tatler and Dr Douglas D Potter. This work has not previously been accepted for a higher degree.

4. June 2015

Signature

Date

Oculomotor and electrophysiological signatures of cognitive distraction during low-level and complex visual tasks

Summary

Distraction during driving is one of the leading contributors to injury and mortality rates in traffic accidents. The aim of this current thesis was to consider 1) whether oculomotor and electrophysiological metrics could act as markers of cognitive distraction; 2) whether decrements in hazard perception performance caused by secondary cognitive task demand are to some extent due to cognitive load interfering with processes of alerting, orienting, inhibitory control and visual search; 3) what elements of secondary cognitive tasks have the greatest impact on hazard perception performance; and 4) whether the susceptibility of previously identified markers of cognitive distraction are affected by primary task difficulty.

Over the course of four Experiments we recorded the effects of secondary cognitive task demand on behavioural, oculomotor and electrophysiological metrics during a variety of low-level and complex visual tasks.

Taken together the experiments of this thesis have demonstrated that secondary cognitive task demand interferes with not just one but every component process of hazard perception performance that was examined. Next, this research has demonstrated that measures such as blink rates, saccade peak velocities, the spread of fixations along the horizontal axis as well as reductions in alpha and beta power output may be reliable indicators of secondary cognitive task demand regardless of the type of primary task. Finally we have shown that the co-registration of eye movements, EEG and ERP measures is a viable method with which to study the cognitive processes involved in visual processing within low level and complex visual tasks.

Chapter I

The importance of understanding driver distraction

Inattention has been found to be one of the leading causes of crashes in real-life driving situations and is therefore a genuine risk to human life (Liang & Lee, 2008; Liang, Reyes & Lee, 2007; Bergasa et al., 2006; Treffner & Barret, 2004, Trick et al., 2004). In 2012 it was estimated that distraction-affected crashes resulted in 3,328 deaths and over 421,000 injuries in the United States alone (National Highway Transportation Safety Administration, VTTI). Results from one study, which tracked 100 drivers for a year, showed that up to 80% of crashes and 65% of near-crashes resulted from some form of driver distraction within three seconds preceding the crash (Klauer, 2005). Therefore understanding driver distraction is important for at least two reasons. First, an understanding of the psychology of distraction allows us to better understand how various types of driver distraction influence the manner in which information is sampled, processed and acted upon under load. For example, an understanding of how distraction influences visual sampling strategies might provide better insights into why hazards are not detected as readily when drivers are distracted. Second, if we can characterise any changes in physiological or oculomotor metrics that are associated with periods of distraction, we may be able to use these as objective markers for cognitive preoccupation. Using these markers we might be able to develop a means with which to unobtrusively assess a driver's current state of distraction, therefore increasing driving safety. Understandably there has been interest and research aimed to uncover such markers (e.g., Liang et al., 2007; Brookhuis & Waard, 2010). Distraction can be the result of various causes such as telephoning (Törnros & Bolling, 2005), interacting with an in-vehicle information system (IVIS; Lee, Caven, Haake & Brown, 2001) and even poor visual conditions

(Konstantopoulos, Chapman & Crundall, 2010). Researchers have quantified the variety of different causes for driver distraction into three major categories: Visual, Cognitive and Physical. And although the ultimate outcome of these distractions is the same: an increase in crash risk, the underlying cognitive mechanisms are different (Regan, Lee & Young, 2008; Anstey et al., 2005).

The effect of physical distractions on measures of driving performance

Physical or biomechanical distraction is defined as a period of time in which the driver removes one or both hands from the steering wheel in order to physically manipulate an object (Young & Regan, 2007). The most commonly studied cause of biomechanical distraction in driving situations is the manipulation of hand-held mobile phone devices and results have indicated a significant degradation of driving performance as a consequence (e.g., Matthews et al., 2003). It was once posited that the primary risk in conversing on a mobile telephone was the interference caused by physically interacting with the mobile device (Briem & Headman, 1995; Brookhuis et al., 1991). One study by Serafin et al., (1993) demonstrated that physically dialling a number on a telephone produced greater lateral vehicle deviations than entering the number via a speech interface or conversing on the telephone. However more recent research has provided evidence that the cognitive distraction resulting from conversing on the phone also has a significant impact on driving performance. This argument is supported by studies indicating no difference between hands-free and hand-held devices in terms of the degradation of driving performance (Haigney et al., 2000; Strayer et al. 2003). Although mobile phone use is the most commonly reported cause of physical distraction in driving, there are many other in-vehicle tasks that can result in the same consequences. Stutts et al., (2001) for example have provided evidence that interacting with the CD player or adjusting the radio were amongst the leading causes in distraction-related crashes. Research has also indicated that drivers made significantly more lane deviations and excursions when physically entering an address into a navigation system (Dingus et al., 1995; Tijerina et al., 1998). The major effect of biomechanical distraction on driving performance is believed to stem from the accumulation of lane position errors (Engström et al., 2005). During periods of physical distraction drivers have been found to make fewer micro steering corrections, resulting in less frequent but larger corrections, which can lead to weaving and lane excursions (Godthelp et al., 1984).

However it should be noted that physical distraction seldom occurs in isolation: The act of tuning the radio requires physical and visual resources, whereas dialling a number from memory might require physical and cognitive resources.

The effect of visual and cognitive task demands on measures of driving performance

Both visual and cognitive distractions have been found to affect driving performance in qualitatively different ways (Engström et al., 2005, Benedetto et al., 2011, Miyaji et al., 2009; Liang, Reyes & Lee, 2007). Therefore it is argued that in order to fully understand the effects of visual and cognitive load increases, it is important to examine them independently from each other. However, to begin with it is important to clarify the distinction between visual and cognitive task demand within the field of driver distraction. Visual distraction has been defined as any type of distraction that causes drivers to neglect the road and to focus on another target for extended periods of time (Young & Regan, 2007). Such scenarios usually involve reading commands of an in-vehicle-information-system (IVIS), using the car radio or consulting maps. These types of in-vehicle visual distractions are thought to lead to a time-sharing of visual resources and thus result in visual attention being diverted away from the road (e.g., Lansdown, 2002). However visual task demand can also be manipulated within the primary driving task itself. For instance increasing the amount of visual distractors

(DiStasi et al., 2010) and degrading the quality of visual information in the scene (e.g., rainy or night driving; Konstantopoulos, Chapman & Crundall, 2010) is thought to result in more visual attention resources being occupied with the extraction of relevant visual information (Engström, et al., 2005). Currently it posited that visual distraction can be measured directly through the external behaviour of the driver and in contrast to this cognitive distraction is internal and therefore impossible to observe directly (Liang & Lee, 2008).

Cognitive task demand can fluctuate due to a variety of different reasons such as using auditory e-mail systems, performing math calculation, holding a hands-free telephone conversation and contemplating a previous conversation (Haigney, 1995; Redelmeier & Tibshirani, 1997). In the case of mobile telephones a meta-analysis conducted by Horrey & Wickens (2004) provided evidence that conversing on a mobile phone resulted in significantly longer RTs to hazardous events. More interestingly perhaps was that there appeared to be no difference between hand-held and hands-free devices in terms of distraction (Patten, Kircher, Östlund & Nilsson, 2004).

The effects of visual task demand on driving performance

Both secondary visual tasks and visual occlusion manipulations result in visual attention being diverted from the road and the driver being unable to give an appropriate tracking response (Engström et al. 2005). This in turn leads to prolonged periods of fixed steering wheel angles during which heading errors accumulate, thus resulting in lane weaving and in some cases lane exits (Godthelp, Milgram & Blaauw, 1984). The negative effect of visual task demand on lane keeping behaviour is well documented (e.g. Greenberg et al., 2003) and has been attributed to deficits in driver’s estimation of time-based safety margins. Driving outside of these “safe boundaries” during times of visual distraction typically results in sharp, over corrective manoeuvres that are more dangerous and disruptive compared to straight road driving. Steering wheel reversal rate (SRR) was introduced by Hoffmann and colleagues in order to quantify the effects of secondary tasks on steering behaviour (e.g. McDonald & Hoffman, 1980). More recently SRR was used to assess the effects of different types of in-vehicle displays on steering behaviour. Results indicated that the complexity of visual displays significantly affected SRR (Liu, Schreiner & Dingus, 1999). The effects of visual task demand on steering behaviour have also been described as a disorder or entropy of steering wheel movements (Boer, 2000). Increases in visual load have been related to a reduction of driving speed, which has been interpreted as a compensatory behaviour in reaction to the increase in task demand (Antin et al., 1990; Curry Hieatt, & Wilde, 1975). It has also been demonstrated that secondary visual tasks (e.g. dialling a mobile phone) resulted in a reduced detection of critical traffic events (Greenberg et al., 2003).

The effects of visual task demand on eye movement behaviour

Results from previous research indicated that increases in visual task demand resulted in repeated switching of visual attention between primary and secondary task stimuli (e.g., Victor, Harbluk & Engström, 2005; Sodhi, Reimer & Llamazares, 2002). It has been argued that the observed deficits in driving performance were because only around half the amount of fixations fell within the visual space of the driving task. However RT analyses indicated that when visual attention was directed “in the right place at the right time” the efficiency of processing is not negatively affected (Olsson, 2000). Therefore it was argued that the effectiveness of visual information processing relied on both how much information needs to be processed as well as the amount of available cognitive resources. It seems that when visual task demand is increased and cognitive load is not , the processing of fixated stimuli is not negatively affected. However the time-sharing of visual resources resulting from switching gaze between two visual tasks leads to a significant reduction in the chance of fixating the correct item in the driving scene at the correct time.

Apart from resulting in gaze shifting between primary and secondary tasks, increases in visual task demand have been found to affect individual elements of eye movement behaviour. For instance, in a study conducted by Di Stasi et al. (2010) visual task demand was manipulated by increasing traffic density. Results indicated that this increase in the visual content of the driving scene resulted in slower saccade peak velocities. This result has been interpreted within a mental fatigue account: higher mental fatigue resulting in slower peak velocities. Another finding has been that peak velocities decreased as a function of total time on task (Galley, 1993; DiStasi, 2012). Saccades vary in amplitude, duration and peak velocity (Dodge & Cline, 1901, Dodge, 1917). The relationship between these individual parameters has become to be known as the ‘main sequence’ - a function that describes a systematic increase of saccade durations and peak velocities with increasing amplitudes (Bahill et al., 1975). However, saccade peak velocities are thought to vary independently from saccade durations, as there is currently no mathematical function for linking these to parameters (Becker, 1989). Bahill and colleagues (1975) research on the effects of mental fatigue on eye movements was amongst the first to point out that individual elements of the saccadic eye movement system could potentially be used to identify general psychological states.

More recently, research has indicated that peak velocities were also affected by mental activation (App & Debus, 1998), alertness (Thomas & Russo, 2007), mental workload (Savage et al., 2013; Di Stasi et al., 2010) as well as drug-induced sedation, sleep deprivation and fatigue (Grace et al., 2010; Zils et al., 2005, Schmidt et al., 1979). These findings indicated that saccade peak velocities are especially sensitive to changes in visual and cognitive load and as such could provide a basis of monitoring changes in driver's mental processes in real time.

Increased visual task demand resulted in shorter blink durations (Recarte et al., 2008; Veltman & Gaillard, 1996). Different elements of blinks have been considered as indicators of both fatigue and mental workload. Ahlstrom & Friedman-Berg (2006) examined the effects of workload from the use of weather displays on air traffic controller operations and results indicated a linear decrease of blink durations as a function of visual task demand. Benedetto et al. (2011) examined the effects of interacting with an IVIS on drivers' blink rates and blink durations during a simulated lane-changing task. Similarly to previous research blink durations decreased as visual task demand increased. Interestingly, while blink durations decreased with visual load, blink rates were not affected. However, Fogarty & Stern (1989) argued that decreased blink rates were related to increases in visual task demand, most likely as a compensatory mechanism to cope with the increase in load. This blink inhibition argument is supported by more recent research by Siveraag and Stern (2000), which demonstrated that blink rates decreased as task complexity increased. It has been argued that changes in eye movement metrics such as fixation number, fixation duration, saccade amplitude and gaze position were the result of repeated gaze switching between primary and secondary visual task. This most likely due to the fact that fixations are directed outside of the driving scene more frequently (resulting in larger saccade amplitudes and differing gaze position) and because visual attention is shared between two tasks resulting either in more fixations or shorter fixation durations. However as blink durations are not related to the switching of gaze, this measure has been considered a promising tool with which to unobtrusively evaluate driver visual task demand (Benedetto et al., 2011).

Visual task demand has been found to interfere with signal and event detection. For example, Olsson (2000) showed a negative effect of visual load on drivers' performance on a peripheral detection task. The peripheral detection task is a secondary task in which participants are instructed to respond to a target presented in their peripheral vision. Measuring the number and speed of target responses is thought to provide some insight into assessing drivers' mental workload and visual distraction (Olsson, 2000). In this real-life driving study participants were instructed to perform a variety of different tasks aimed to increase both visual and cognitive load respectively whilst driving on motorway or country roads and performing a simultaneous peripheral detection task. The authors found a dissociation between the effects of secondary visual and cognitive tasks on peripheral detection task performance. High visual task demand led to lower hit rates but no changes in reaction times (RTs) and high cognitive load resulted in slightly reduced hit rates but significantly slower RTs. However it should be noted that performing a simultaneous peripheral detection task whilst driving is not a practical method for assessing driver behaviour in real-life as the task itself places an additional task demand on the driver, which as any secondary visual task diverts resources away from the primary task.

The effects of cognitive task demand on driving performance

Increases in cognitive task demand have been shown to interfere with a variety of different measures of driving performance. In a study conducted by Lamble et al. (1999) participants were on average 0.5 seconds slower to react to the brake lights of a pace car when simultaneously completing a secondary memory and addition task. A large proportion of research in the field of driver distraction has examined the effects of conversing on a mobile phone on driving performance. However, it has been demonstrated that the activation of language comprehension and production centres of the brain can interfere with primary task performance (Just, Keller &

Cynkar, 2008). Therefore in order to examine the effects of cognitive load on driving performance it was necessary to isolate mechanisms relating to cognitive task demand from processes involved in language production and comprehension.

In order to address this issue, Savage, Potter & Tatler (2013) manipulated cognitive load by asking participants to solve riddles during a hazard perception task whilst behavioural, eye movement and electrophysiological measures were recorded. The novel aspect of this experimental manipulation was that participants were not required actively to produce or process verbal information during the hazard perception task as with typical cognitive workload manipulations. Similarly to previous research, behavioural results indicated that increases in cognitive load, resulted in slower RTs to hazards, but did not result in an increase in the chance of missing a hazard. Finally, results indicated, that there was a significant increase in responses to non-hazardous stimuli (i.e. false alarms) which indicated that the incoming visual information may not have been processed as effectively as when full cognitive resources were available. This interpretation was supported by the observations that increases in cognitive task demand interfered with event detection performance on a peripheral detection task (Olsson, 2002) as well as the ability to detect hazards across the visual scene (Recarte & Nunes, 2003; Victor, Harbluk & Engström, 2005).

In general results indicate that increases in cognitive task demand have little or no effect on lane keeping performance (Horrey & Wickens, 2004). However one study by Rakauskas and colleagues (2004) showed an effect of cognitive load on steering wheel activity. Another study by Alm & Nilsson (1994) indicated that increased cognitive task demand resulted in changes in mean lane position but not in variability. Taken together these results suggest that cognitive task demand influences driver's estimation of safety margins rather than reducing lateral control of the vehicle.

In a study conducted by Patten et al. (2004) it was found that hands-free phone conversations had no effect on driver's speed (longitudinal control). In contrast to this holding a conversation via a hand-held device resulted in a significant reduction in speed. The difference between hand-held and hands-free devices in terms of speed control is thought to reflect a difference in conscious awareness of the distraction resulting from each device. In other words when the phone is hand-held drivers become consciously aware of the increased crash risk and thus reduce their speed in order to maintain an acceptable risk level (Engström et al., 2005).

Research by Miyaji et al. (2009) indicated that secondary verbal and arithmetic tasks resulted in an increase in head movements, which has typically been interpreted as a compensatory behaviour in order to gain a wider field of view when cognitive task demand was high.

The effects of cognitive task demand on eye movement behaviour

A study conducted by Recarte & Nunes (2003) demonstrated that a wide variety of secondary mental tasks lead to gaze concentration towards the centre of the road (reduction in variability of gaze position) as well as a reduction in visual-detection performance. Furthermore the addition of a secondary cognitive task resulted in increased pupil diameter and reduced inspection frequency of mirrors and speedometers. However, these effects occurred without a change in lane position variability or in driving speed (Recarte & Nunes; 2003). Oculomotor metrics have been found to vary as a result of secondary cognitive task demand manipulations. Harbluk, Noy & Eizenman (2002) varied the complexity of the secondary mobile telephone conversation, which resulted in a concurrent decrease of saccade numbers and an increase in the percentage of time spent fixating on the centre of the road.

More recently it has been suggested that the percentage of time fixating on the central region of the road increases as a function of secondary cognitive task complexity: More complex tasks lead to a greater proportion of time spent fixating closer to the middle of the road (Reimer, 2009; Victor, Harbluk & Engström, 2005).

A possible explanation for an increased concentration of gaze around the centre of the visual scene has been that cognitive task demand may be interfering with anticipatory eye movements towards tangent points of curves and intersections, thus leading to a reduction in overall spread of fixations. A study examining the effect of working memory load on eye movement behaviour during real-life driving has shown that increased working memory load resulted in a significant reduction of anticipatory eye movements when approaching a curve (Lehtonen, Lappi & Summala 2014). Drivers fixate upon the tangent point of the curve in order to extract the most amount of visual information from the bend in order to control steering behaviour and to identify hazards (Land & Lee, 1994). Under normal circumstances drivers look at the tangent point and occlusion point of the curve but as cognitive task demand increases, visual anticipation is decreased resulting in more fixations landing within the vicinity of the centre of the road.

Previous research examining the effects of purely cognitive based preoccupation on hazard perception performance indicated that, contrary to visual task demand manipulations (DiStasi et al., 2010), increases in cognitive task demand resulted in faster saccade peak velocities (Savage, Potter & Tatler, 2013). The dissociation between the effects of visual and cognitive task demand on saccade peak velocities indicates that this particular eye movement measure may be of particular interest to researchers attempting to determine both signatures of secondary cognitive and visual load.

Blink rates are a good indicator of mental fatigue and workload (Fukuda, Stern, Brown & Russo, 2005; Stern, Boyer & Schroeder, 1994). This is primarily due to the observation that blink rates increased as a function of time on task. As mentioned earlier, increases in visual task demand resulted in significantly shorter blink durations. Analyses of blink rates within the hazard perception study of Savage et al. (2013) revealed that high cognitive load was associated with an increase in blink rates within individual trials. A study by Recarte and Nunes (2002) has shown that blink rates not only increased as a function of time on tasks but also increased more rapidly when cognitive task demand was high. Taken together these results indicate that increases in blink rates may be due to fatigue as well as cognitive task demand. Ryu & Myung (2005) analysed changes in the time between blinks resulting from including either a secondary tracking or a mental arithmetic task and found that only increases in tracking task complexity affected the time between blinks.

The effects of cognitive and visual task demand on electrophysiological measures in driving scenarios

Although the hazard perception task is a commonly used paradigm in studying the perceptual elements involved in driving, currently not much is known about the electrophysiological processes underlying the skill of hazard perception. In order to better understand the effects of driver distraction, previous research has examined the effects of cognitive task demand on simulated driving behaviour by analysing differences in EEG activity (Lin, Ko & Shen, 2009). Metrics which have been found be related to cognitive distraction were theta (4-8 Hz), alpha (8-14 Hz) and beta (14-35 Hz) frequency band activity (Lin, Chen, Ko & Wang, 2011). Theta and beta band activity in frontal areas of the brain are associated with cognitive processes such as decision-making, working memory, problem solving and judgment (Lin et al., 2011). Oscillations in the alpha band are the most commonly recorded frequencies in studies examining attention processes (Schier, 2000; Klimesch, Doppelmayr, Russegger, Pachinger & Schwaiger, 1998, Wolfgang, 1999). Typically increases in cognitive workload resulted in a significant decrease or desynchronization of alpha band activity (Klimesch et al., 1999; Wolfgang, 1999) and a significant increase or synchronization of theta activity (Tulving, Kapur, Craik, Moscovitch & Houle, 1994). Savage et al. (2013) examined the effects of cognitive workload on hazard perception performance using EEG. Results showed a significant increase in frontal and decrease in occipital theta activity in high compared to low cognitive task demand conditions. Average differences in theta activity were calculated overall between both high and no cognitive load conditions, therefore this particular measure may give a good indication as to the overall (tonic) difference in cognitive workload on a trial-by-trial basis. Previous research, using EEG as a means with which to assess alertness (Lal & Craig, 2002; De Waard & Brookhuis, 1991) has demonstrated that delta and theta activity increased significantly with driver fatigue. Furthermore other factors such as anxiety and mood states were found to affect fatigue and are associated with similar neurophysiological signatures of fatigue, such as increased theta and delta band activity at anterior, central and parietal regions of the brain (Lal & Craig, 2002).

Previously ERP components such as the P300 have been shown to be sensitive to some perceptual aspect of stimulus evaluation such as contrast or intensity (Coles, Smid, Scheffers & Otten, 1995). Furthermore, target probability and intensity increase P300 amplitudes in both visual and auditory oddball sensory detection tasks (Polich, Ellerson & Cohen, 1996). A flight simulator study by Kramer and colleagues (1987) demonstrated that performance data (RTs & accuracy) in a secondary auditory detection task were not affected by the primary simulated flight task. However, the peak amplitude of the P300 component was sensitive to manipulations in flight task difficulty. It was therefore argued that, if sensitive to external task demands, ERP components could be a useful tool with which to assess primary task difficulty, especially as they require no overt responses by participants (Mangun & Hillyard, 1995). In a simulated driving task Baldwin et al. (2003) examined the effect of traffic density on midline central and parietal P300 amplitudes. Although the authors found a decrease of amplitudes corresponding with increased traffic density, these effects did not reach significance. However P300 amplitudes have been demonstrated to be a reliable measure of workload when measured in response to a secondary oddball task. For instance, Janssen & Gaillard (1984) were able to discriminate primary task demand resulting from three distinct road environments by measuring P300 amplitudes in response to a secondary oddball task. It was reasoned that as primary task demand increased (thus demanding more cognitive resources), participants' ability to form patterns of expectancies in regards to target and novel sounds was interrupted and subsequently P300 amplitudes were decreased (Wickens, Isreal & Donchin, 1977).

Apart from externally (visually) driven task demand increases, internal (cognitive) factors such as intoxication and distraction have been found to lead to a significant reduction in amplitude of the novelty P300 signals (Rakuaskas et al., 2005). In this study the experimenters evaluated the effects of various types of visual and cognitive distractions such as conversing on a cell phone, interacting with an IVIS as well as being intoxicated (Blood Alcohol Content = 0.08) on P300 amplitudes in response to a secondary oddball task. The authors found that being distracted by a conversation as well as being intoxicated (and to a lesser extent interacting with an IVIS) led to a significant reduction in the evaluation of sudden and unexpected stimuli. More recently, a driving steering simulator (DSS) study by Wester and colleagues (2008) examined the impact of performing a secondary auditory oddball task on primary task performance (lane keeping) as well as P300 amplitudes. P300 amplitudes were compared between conditions in which the primary (DSS) and secondary (auditory oddball) tasks were either presented individually or simultaneously in order to assess their mutual interference. When both tasks were performed at the same time, P300 amplitudes were significantly reduced in comparison to when the auditory oddball task was performed individually. Interestingly, the reduction of ERP amplitudes occurred although performing both tasks simultaneously did not result in a decrease in lane keeping ability. This study suggested that primary task performance was not affected because, as analyses of brain activity indicated, cortical processing of the irrelevant, potentially distracting secondary task was reduced (Wester et al., 2008).

Deiber and colleagues (2007) combined both approaches of time course and frequency analyses. In this experiment theta band frequency was recorded to investigate increases in workload resulting from a mental arithmetic task. The authors demonstrated that frontal theta band activity increased as a function of mental workload. This is supported by findings from Jensen & Tetsche (2002), which suggested that frontal theta activity is positively correlated with working memory load in a classic working memory paradigm.

In a driving simulator study conducted by Lin et al. (2011) the experimenters examined the temporal relationship between the onset of cognitive distractors and theta as well as beta frequency band fluctuations. Results indicated bursts of frontal theta and beta activity shortly after the onset of the mental arithmetic task. These findings imply that the secondary tasks induced more event-related theta activities because more attentional resources were required to simultaneously compute two tasks (Onton, Delorme & Makeig, 2005).

Oculomotor and neurophysiological signatures of cognitive task demand

Research from the field of clinical neuropsychology has attempted to construct a unified test with which to distinguish patients with and without brain damage. However researchers in this endeavour soon realised that due to the very complex, interactive nature of cognitive functions, the neuropsychological tests designed to test higher-level mental processes were not entirely able to isolate individual cognitive functions (Lezak, 2004).

Eye movements have long been studied as indicators of functional disturbances in brain systems that may be associated with psychopathology in schizophrenia and bipolar disorder (Diefendorf & Dodge, 1908; Fukushima et al., 1988; Tien et al., 1996). Studies have typically reported impaired performance on smooth pursuit and saccadic tasks such as the antisaccade task. The antisaccade task requires participants to supress reflexively orienting their visual attention to a sudden onset target in favour of planning a volitional eye movement, usually to a mirror location. More recently antisaccade performance has been examined as a potential indicator of a wide variety of different psychiatric and neurologic disorders such as attention deficit and hyperactivity disorder (ADHD), obsessive-compulsive disorder (OCD), affective disorder, autism, Parkinson's disease, Alzheimer's disease and Huntington's disease (see Hutton & Ettinger, 2006 for review). Similarly EEG has been used as a tool with which to assess ADHD (Bresnahan et al., 1999), mood disorders (Harmon-Jones & Allen, 1997), schizophrenia (Stevens et al., 1982; Gattaz et al., 1992), epilepsy (see Hoppe et al., 2009 for review) & bipolar disorder (Allen et al., 1993; Clementz et al., 1994). As distraction has been shown to influence both eye movement and EEG metrics, it is argued that changes in certain measures could be utilized as an index of cognitive preoccupation.

Taking into account the ever-increasing possibilities of in-vehicle distractions through smartphones and IVIS the need for more advanced technologies to detect driver distraction are apparent (Schier, 2000). Traditionally researchers have relied on four categories of measurements to assess drivers' current cognitive state: subjective estimates, primary and secondary task performance and physiological measures (Liang & Lee, 2008; Zhang, Owechko & Zhang, 2004). However it becomes clear that in real life driving situations none of these measures would provide a practical solution for assessing driver cognitive distraction as they are either intrusive or increase cognitive task demand in themselves. Therefore, as with assessing visual distraction, it will be of importance to distil signatures (physiological indicators), which can be obtained unobtrusively and without increasing secondary task demand. Previously it has been argued that increases in cognitive load could only be observed as manifestations in behaviour (Liang & Lee, 2008), however more recently research has been interested in determining physiological markers of cognitive distraction (Savage, Potter & Tatler, 2013; Liang, Reyes & Lee, 2007, Bergasa et al., 2006). As eye movements are intimately linked to attention (Hutton, 2008), one approach to this has been to monitor changes in eye movement behaviour between varying levels of secondary cognitive task demand. Many of the papers discussed so far relate changes in visual and cognitive task demand to changes in eye movements. More recently researchers have considered how eye movements can be used to detect distraction in real time (Liang, Reyes & Lee, 2007, Zhang, Owechko & Zhang, 2004; Strayer & Johnson, 2001; Strayer, Drews & Johnson, 2001; Recarte & Nunes, 2000; Rantanen & Goldberg, 1999; May, Kennedy, Williams, Dunlap & Brannan, 1990). However the major problem is that the mental state of drivers is not observable and therefore no single measure is thought to be able to index cognitive distraction precisely (Zhang, Owechko & Zhang, 2004). In order to determine factors that may index distraction in driving situations, scientists have typically employed dual-task paradigms whilst tracking eye and head movements, as well as physiological (e.g., heart rate, galvanic skin response) and electrophysiological (EEG) metrics. The goal of this collective research effort is to combine as many possible metrics as classification features for pattern recognition in support Vector Machines (SVMs – supervised learning models associated with algorithms for feature and event detection) that in future could asses and alert distracted drivers thus reducing crash-risks.

We acknowledge that recording electrophysiological measures such as EEG during real-life driving may not be a practical way to gauge mental workload. However it will be of great benefit in laboratory experiments to determine how increases in cognitive task demand affect the allocation of cognitive resources between both primary and secondary task demand. There are several advantages for utilizing EEG for the detection of distraction (Lin et al., 2009). Firstly EEG is a non-invasive technology, which can be applied repeatedly on participants with no health risk or substantial methodological restrictions (Teplan, 2002). Secondly, EEG has extremely high temporal resolution, which allows for the evaluation of changes in both event related and global task demand. In a study by Galán & Beal (2012) the authors suggested that EEG might also be a valuable tool in assessing cognitive workload and predicting the performance in a math-solving task.

Which elements of hazard perception are most susceptible to changes in cognitive load?

As research on driver distraction has been conducted with such a large variety of different methods and techniques it is difficult to generalize findings across studies (Hosking, Young & Regan, 2005). Work employing hazard perception paradigms include highly complex and relatively uncontrolled visual scenes (videos of real driving scenarios). This lack of control over primary visual task demand may prove to be an issue when attempting to isolate the effects of cognitive load. The hazard perception task requires a specific set of skills, such as the ability to efficiently search for targets amongst distractors (visual search), the ability to quickly fixate upon sudden onset stimuli which may turn out to be dangers (orienting), as well as the ability to supress orienting (or re-orienting) of attention to task irrelevant distractors (inhibitory control). In order to fully understand the effects of cognitive preoccupation on hazard perception performance, it is important to consider what aspects of the task are particularly susceptible to cognitive distraction. One way of addressing this issue is to examine the effects of cognitive distraction in simple paradigms that isolate key aspects of the hazard perception task: orienting (prosaccade task), inhibitory control (antisaccade task) and a low-level visual search task.

Examining the effect of cognitive task demand on these three distinct sub-processes may inform our understanding of which element of hazard perception performance is most impacted by variations in cognitive load. Furthermore, by considering the influence of cognitive distraction in paradigms covering three well-established aspects of visual attention, it would be possible to compare changes in eye movement and electrophysiological measures between complex and visually low-level tasks. If changes in oculomotor and electrophysiological measures resulting from increases in cognitive task demand are similar between complex and simple visual tasks, it could be argued that these metrics are indicative of variations in cognitive task demand in general. Most importantly, by isolating the individual components of the hazard perception task and examining their susceptibility to cognitive load, we may be able to infer which elements of the more complex task are affected by distraction.

Processes involved in alerting, orienting and inhibitory control

Traditionally two paradigms used to examine both reflexive orienting and inhibitory control of visual attention, have been the pro and antisaccade tasks (Hallett, 1978). In most standard prosaccade task participants are required to fixate in the centre of the screen with two empty placeholders either side of a central fixation point. The central fixation point disappears and a target appears in one of the two peripheral locations. Participants are required to fixate upon the sudden-onset target as quickly as possible and press a button. The antisaccade task utilizes the same experimental procedure however participants are instructed to fixate on the opposite placeholder to the one containing the sudden onset target or to an unmarked location of equal distance from the centre but in the opposite direction of the target.

Prosaccades are thought to reflect reflexive shifts of (overt) visual attention. The most commonly recorded measures in the prosaccade task have been saccade latency, amplitude and peak velocity; however other metrics such as final landing position and amount of corrective saccades have been found to be informative (Fischer & Webber, 1993; Pratt, 1998). Saccade latency is the time from the onset of the target to initiation of the first eye movement and therefore is thought to reflect the speed at which reflexive saccades are initiated. In the prosaccade task the average distance from the final fixation to target (gain) is associated with how well saccade end points are calculated and motor programs were executed.

Prosaccades towards a sudden onset target can be influenced by a wide variety of different cognitive processes resulting from subtly varying task instructions (Mosimann, Felblinger, Colloby & Muri, 2004) to manipulating the time between central cue offset and target onset. By varying the temporal relationship between the offset of the central fixation cue and the onset of the target cue it is possible to create both gap and overlap versions of the standard prosaccade task. The gap version of the prosaccade task traditionally has a 200 ms gap between the disappearance of the central fixation point and the appearance of the target. The step version of the task reduces the gap between offset and onset to zero so that the target appears to "step" from the centre to the target location. Past research has produced consistent results indicating that prosaccade latencies were significantly reduced in gap over step trials (e.g. Fischer & Weber, 1992). One study has also shown that saccade peak velocities were faster in gap conditions (Pratt, 1998). It has been argued that the gap between the disappearance of the central fixation point and the appearance of the target provides participants with enough time to disengage attention at the central location before orienting to the target location, thus resulting in faster latencies. In overlap trials, attention is thought to be engaged on the central fixation point at the time of the target onset. Increased latencies in comparison to gap trials are thought to be the result of participants having to disengage attention prior to being able to orient to a new location (Fischer & Breitmeyer, 1987; Fischer & Weber, 1993). An alternative account has been that the disappearance of the central fixation point serves as an alerting signal, which indicates the imminent arrival of the target thus decreasing latencies (Lorenz, Oonk, Barnes, & Hughes, 1995). Typically first saccade latencies are thought to reflect the speed of orienting and gain the general accuracy.

The antisaccade task requires that the reflexive response of saccading toward a sudden onset peripheral target is suppressed and additionally that a saccade in the opposite direction is planned and executed. Similarly to the prosaccade task, the metrics of most interest are: saccade latency, amplitude and peak velocity. Measures such as the proportion of antisaccade errors, error latency and correction latencies have also been found to be of interest as they reflect the behaviour produced when inhibitory control fails to suppress the reflexive response. Antisaccade latencies indicate the time needed to supress the (false) initial prosaccade and program the (correct) volitional antisaccade. Antisaccade errors have typically been taken as evidence of how efficiently inhibitory control processes are at supressing prepotent prosaccades.

A fundamental part of human behaviour is the need to supress constant reflexive orienting in favour of carrying out goal directed behaviour. Especially in driving it is crucial to be able to ignore unwanted distractions in favour of focusing on the road. This is thought to require processes of inhibitory control, which are isolated in the antisaccade task. Healthy participants typically have a significant error rate in antisaccade tasks in that they often reflexively orient towards the sudden onset stimuli. These erroneous prosaccades are, in most trials, followed by a rapid corrective antisaccade in the direction of the opposite placeholder (Tatler & Hutton, 2007).

Two basic findings have been that latencies of incorrect prosaccades are usually in the range of standard prosaccades and that latencies of correct antisaccades are generally 100 ms longer than correct prosaccades (e.g. Evdokimidis et al., 2002). It has been argued that the sudden onset of the target produces an automatic motor program for a prosaccade towards the target's location, which needs be inhibited in order for a volitional (endogenous) antisaccade program to be executed. Incorrect prosaccades are produced when processes of executive function fail to inhibit or cancel the automatic program. This account is supported by the observation that correct and incorrect prosaccade latencies are the same. Correct antisaccade latencies are significantly increased over correct prosaccade latencies because the necessary inhibitory processes are thought to be effortful and time consuming (Olk & Kingstone, 2003). Therefore the execution of a correct antisaccade requires two distinct sub-processes: (1) inhibition of reflexive reorienting and (2) volitional control of the saccadic eye movement system (Everling & Fischer, 1998). The interpretation that saccade programs are written in parallel is supported by competitive race accounts of antisaccade performance (Munoz & Everling, 2004; Hutton & Ettinger, 2006). These accounts postulate that, in an antisaccade task, the sudden onset of the target results in a competition between the exogenously triggered prosaccade and the endogenously planned antisaccade (Hutton, 2008). For a correct antisaccade to be executed the corresponding program must be written before the competing prosaccade can be initiated thus cancelling it. Conversely, if the incorrect prosaccade program is "faster", it is initiated first followed by a corrective saccade (Massen, 2004). More evidence for the parallel nature of saccadic programming is that average latencies of corrective saccades are shorter compared to correct antisaccades (typically around 130 ms for corrective saccades). If saccade programs were written in series one would expect corrective saccade latencies to be the same length as correct antisaccade latencies as the correct antisaccade could only be initiated once the false prosaccade had been executed (and not inhibited). These results however suggest that both prosaccade and antisaccade programs were written in parallel and that there is an overlap between the initiations of both programs. Antisaccade performance is therefore thought to depend on processes of executive function such as inhibitory control, planning and monitoring (Unswort, Engle, & Schrock, 2004).

As with the prosaccade task there are a wide variety of cognitive processes, which have been shown to affect antisaccade performance. Introducing a 200 ms gap between the central fixation offset and the target onset for instance, has been shown to increase antisaccade error rates. In line with competitive race accounts, a gap conditions produces faster prosaccade latencies either through a disengaging or an alerting mechanism, which results in the prosaccade program arriving at the required threshold for activation more quickly. Another finding has been that correct antisaccade latencies were roughly 25 ms faster in gap trials than in overlap trials which was a smaller difference than that observed between overlap and gap prosaccade trials (40 ms). It has been argued that the reduced benefit for gap trial antisaccades over gap trial prosaccades was due to the fact that certain processes of disengaging may not have been involved to the same extent in endogenously guided saccades as they were in exogenously guided eye movements (Reuter-Lorenz et al., 1995).

It has been demonstrated that variations in secondary cognitive load affected performance in both pro and antisaccade tasks (Stuyven et al., 2000; Godijn & Kramer, 2008). Although antisaccades are more susceptible to an executive interference task, prosaccades are also affected. It has been argued that antisaccade performance was affected due to the fact that antisaccades require controlled processing. Therefore, increasing executive load interferes with these processes. Furthermore, it was demonstrated that endogenous prosaccades were also prone to dual-task interference. This result was of particular interest as it suggests that controlled saccade execution, without the need to inhibit a prepotent response, relies on top-down mechanisms, which are susceptible to variations in cognitive load (Stuyven et al., 2000). These findings indicate that the extent to which any saccade can ever be truly "reflexive" is debatable. In a study by Roberts et al. (1994) participants were instructed to perform a concurrent secondary arithmetic task whilst antisaccade performance was assessed. Results indicated that high working memory load lead to a significant increase in both correct antisaccade latencies as well as error rates. Similar experiments have reported that antisaccade performance detriments vary as a function of working memory load (Mitchell, Macrae & Gilchrist, 2002). By employing three variants of the n-back task (a task which typically requires participants to monitor a string of presented items and respond when two items which are separated by "n-steps" are the same) previous authors were able to categorically manipulate working memory showing that antisaccade performance was most impaired in the 2-back condition followed by the 1-back and least impaired in the 0-back condition. It was reasoned that the inhibition of the incorrect prosaccade as well as the programming the correct antisaccade requires working memory resources. As working memory has a finite capacity, including a secondary concurrent working memory task diverts resources away from the primary goal maintenance tasks resulting in increased error rates and correct antisaccade latencies.

Electrophysiology associated with the control of eye movements

Previous research in the field of lesion studies, behavioural testing, functional-neuroimaging and animal neurophysiology has identified a number of brain regions that are involved in the control of fixations and saccadic eye movements. These include regions in the cerebral cortex, basal ganglia, thalamus, superior colliculus (SC), brainstem reticular formation and cerebellum (see: Munoz & Everling, 2004 for review). Other cortical sites include the lateral intraparietal area (LIP) in the posterior parietal cortex (PPC) due to its function as an interface between sensory and motor processing (Andersen, 1997; Colby & Goldberg, 1999), frontal eye fields (FEF) due to their vital role in executing voluntary saccades (Dias & Segraves, 1999; Gaymard et al., 1999), the supplementary eye fields (SEF) due to their involvement in the internally guided decision-making and sequencing of eye movements (Stuphorn, Taylor, & Schall, 2000) and the dorsolateral prefrontal cortex (DLPFC) due to its role in executive function, spatial working memory and inhibitory control (Guitton, Buchtel, & Douglas, 1985; Fuster, 1997). Research has demonstrated that the superior colliculus together with a variety of subcortical structures play a large role in determining the position of targets and executing saccades towards them (Moschovakis & Highstein, 1994; Schall, 1995). Furthermore, the superior colliculus receives connections from a large variety of cortical areas including the parietal cortex and frontal regions such as the FEF and SEF. These have been shown to receive projections from V1 and other areas of the visual cortex (Johnston & Everling, 2008). This network interacts with other cortical areas such as the DLFPC, which is associated with executive functions such as inhibitory control, decision making and working memory and can therefore influence the processes involved in “deciding” where to fixate next. Furthermore, correct antisaccade performance may be associated with SEF as well as frontal lobe activity (Pierrot-Deseilligny et al. 1991; Stuphorn, Taylor, & Schall, 2000).

A variety of studies have compared event-related potentials prior to prosaccades and antisaccades (Brickett et al., 1984, Evdokimidis et al., 1996; Everling et al., 1997). Findings suggested a lower positivity at central parietal sites prior to antisaccades compared to prosaccades, an indication that frontal (executive) mechanisms were inhibiting reflexive prosaccades (Evdokimidis et al., 1996). Furthermore, results indicated significantly greater negativity at central electrodes prior to antisaccades as compared to prosaccades. This was interpreted as an activation of the SEF prior to antisaccades, which had previously been demonstrated in primate studies (Amador et al., 1998, Schlag-Rey et al., 1997).

A study conducted by Everling and colleagues (1997) compared event-related potentials associated with correct and incorrect responses in a cued antisaccade task. Correct antisaccades and incorrect prosaccades were both associated with a negative potential around the time of stimulus onset at dorsomedial frontal sites. Interestingly, the event related potentials prior to correct antisaccades were more negative than to correct prosaccades. Furthermore this study indicated that the execution of a correct antisaccade was preceded by a shift of negative potential in the parietal hemispheres. This shift of negative potential started in the hemisphere contralateral to the target and travelled to the hemisphere ipsilateral to the target.

In humans, the parietal cortex is involved in motor control as well as the processing and perception of action related information (Fogassi & Luppinio, 2005). Structural damage to parietal areas in humans has been found to produce behaviour that is characterized by the inability to attend and respond to objects in the visual field (Halligan & Marshall, 1994). Furthermore parietal cortex has been found to play an integral role in the “vision for action” system (Milner & Goodale, 1995, 2004), which has been described as an automatic conversion of visual information into motor commands.

Processes involved in visual search

Successfully performing any visual task requires the encoding of a large field of view with retinas that have a very small area of high visual acuity. To this end humans, like many mammals must use eye movements in order to direct their high-resolution fovea towards potential target locations (Carpenter, 1994, Liversedge & Findlay, 2000). Evolutionarily, good search performance is important for survival and it becomes clear that in order to survive we do not only need to know what to fixate but also when to fixate upon certain items in our environment. This is especially true in dynamic tasks such as driving where fixating upon something at the wrong time can result in the oversight of something else, which may result in a traffic accident. Visual search has been described as one of the most profitable paradigms for studying the allocation of attention within visual scenes (Wolfe, 1994).

Within a standard laboratory visual search paradigm, participants are required to search for a target item, typically present on 50% of trials, amongst distractor items. Distractor items can share none, one or multiple characteristics of the target item. The total number of items participants are required to search through is called the set size. Participants are asked to make a decision about whether the target was present or absent in the search array. There are many variations of visual search paradigms ranging from the search for simple singleton features (e.g. Müller, Heller & Ziegler, 1995) to complex arrays (e.g. Beck, Lohrenz & Trafton, 2011) and high-level configural differences (Gerhardstein et al., 2002). Previously research has examined the interaction of top-down and bottom-up processes involved in visual search by manipulating the similarity between the target and distractors as well as the set size and the structure of the items within the array.

The most commonly recorded measures of performance in visual search tasks are the percentage of correct responses and participants RTs. This is because these measures are thought to reflect the efficiency and speed of search. RTs are usually analysed as a function of set size. This produces two functions one for target present trials and one for target absent trials.

For types of search that do not require participants to identify the target by a feature singleton, the most consistent result is that RTs increased as a function of set size. This has been regarded as a measure of cost related to processing each additional distractor (Wolfe, 1994). Typically RTs are longer in target absent compared to target present trials (e.g. Harvey & Gilchrist, 2005) and the slope of the RT x set size function is steeper in target absent trials. This is most likely due to the following: in target present trials the target can either be fixated upon early (within the first few fixations) or late (within the last few fixations) and anywhere in between. Therefore on average attention will need to be allocated to only half of all items in the display before locating the target. However on absent trials attention will have to be directed to every single item in the array before the targets absence can be confirmed. Hence, the cost of increasing the number of distractor items is twice as large in target absent as compared to target present trials. These results indicate a self-terminating search in which participants allocate attention from one item to the next until such a point when the target is either identified or all of the items have been checked (Sternberg, 1969;

Treisman & Gelade, 1980). These findings are consistent with early models of attention such as feature-integration theory, which assume that if a target contains a conjunction of two or more separate features, attention is allocated serially to each individual item in the display until the target is identified or every item has been searched (Treisman & Gelade, 1980).

Optimizing overall performance across target present and absent trials is thought to rely on varying the tendency to say "yes" or "no" based on prior expectations about the prevalence of the target. If over the course of an experiment, the participant has learned that the target is present in 99% of trials, then saying "yes" (target present) more frequently will increase the chance of making a correct decision. Previous psychophysical experiments have demonstrated the extent to which observers alter their propensity to make decisions based on prior probability of auditory, visual and even taste signal occurrences (Tanner, Swets & Green, 1956; Linker, Moore & Gallanter, 1964). Research has also examined the effect of target prevalence on fundamental aspects of search behaviour aside from the decision criterion. Gur and colleagues (2003) utilized medical images containing lesions in order to study the effect of target prevalence on search performance. Results indicated that the probability of the target being present did not alter the observer's ability to detect the lesion but did however alter the observers' confidence of having made the correct decision. Lower target prevalence resulted in lower observer confidence that the target was present (Gur et al., 2007). It has been argued that errors with low target prevalence can be attributed to two separate processes relating to a classic decision criterion shift (Green & Swets, 1989) as well as alterations in quitting thresholds (Wolfe & Van Wert, 2010). When prior probability is low the target is more rare and observers have been shown to stop searching for the target sooner, resulting in more missed targets. One study by Fleck and Mitroff (2007) suggested that missing the target in low target prevalence conditions was due to response execution errors resulting from fast responses and not perceptual or identification errors. However these types of errors cannot account for all the errors occurring in low target prevalence conditions. Furthermore, follow up studies demonstrated that changes in decision criterion were necessary to account for the increases in missed targets (Van Wert, Horowitz & Wolfe, 2009). We argue that visual search in driving situations contains times when hazards are present and when they are not present. Examining the effects of cognitive load on both target present and absent trials in simple visual search tasks may help determine which aspect of visual search is affected in more complex driving situations.

In order to better understand the processes that mediate between the display onset and the resulting manual response, researchers have monitored eye movements during visual search (Findlay, 1997, Hooge & Erkelens, 1999). Most of the early resulting models of eye movement behaviour during visual search have typically focussed on the bottom-up processes involved in the allocation of fixations to items in a display (Itti & Koch, 2000). These saliency-based approaches postulated that individual features of each item are deconstructed and compared to the individual features of the target. Therefore if the target was a blue ball, everything in the display that was either blue or circular will have gained enhanced salience. This is the basic principle by which attention (Wolfe, 1994) or saccades (Findlay & Walker, 1999; Itti & Koch, 2000; Wolfe & Gancarz, 1996) is allocated to items that are most similar to the target. However research by Buswell, (1935) revealed that fixations in a visual scene can vary depending on the goals and motivation of the viewer and that the same person viewing the same scene can produce a different pattern of eye movements. These findings were amongst the first to demonstrate that eye movements are intrinsically cognitive in nature (Hayhoe & Ballard, 2005) and that the processes controlling saccadic eye-movements were not purely bottom-up.

To investigate the notion that scan paths do contain a systematic, cognitive, strategic element rather than being reliant on random processes, Gilchrist & Harvey (2006) examined changes in fixation patterns across three search arrays all differing in their degree of structure. It was argued that if saccades were allocated to locations at random, then changing the structure of the array should not change overall fixation patterns. Results however suggested with regular, grid-like displays, participants made more horizontal than vertical saccades. Furthermore the disruption of the grid structure modulated but did not eliminate this systematic component. This uneven distribution of saccades across angles indicated a more strategic behaviour in general (Gilchrist & Harvey. 2006). Another factor that contradicts purely saliency-based approaches to saccadic eye movements is that memory processes have been shown to influence search behaviour on a number of different levels (Shore & Klein, 2000). In this research the authors presented evidence that factors such as perceptual learning, trial-to-trial priming and within trial tagging all affect search performance in different ways. Trial-to-trial priming refers to the repetition of a previous trial's target identity, target location and distractor identity and locations. Typically, priming results in a significant increase in search performance as well as a reduction in search time (Maljkovic & Nakayama, 2000; McPeek et al., 1999). Perceptual learning refers to the development of task specific skills in experts versus novices. The distinction between experts and novices is found in everyday-tasks such as driving (Chapman & Underwood, 1998) but has also been demonstrated in laboratory settings. In the context of search there are a variety of experiments indicating that both task and stimulus-specific skills are learned and retained for long periods of time (e.g. Fisk & Hodge, 1992). Within trial tagging refers to the marking of previously inspected items and has been shown to greatly reduce the re-inspection of previously visited stimuli (Shore & Klein, 2000). Memory and attention are thought to form an iterative and interactive network (Cowan, 1995, Desimone & Duncan, 1995): explicit memory is influenced by what we attend (James, 1890; O'Regan, 1992) and what we attend to is generally informed by previous experience. Therefore if memory mechanisms are involved in the processes guiding where we look, it is feasible to assume that cognitive distraction may also interfere with search behaviour.

A vital aspect of any natural task is learning where to look (Hayhoe & Ballard, 2005). Especially for driving, the ability to develop adequate attentional models in order to guide visual search to potential hazards or other locations within the driving scene that contain vital information is crucial (Crundall & Underwood, 1998; Deery & Fildes, 1999; Underwood, Chapman, Bowden & Crundall, 2002). For instance, Shinoda et al., (2001) showed that 45% of all fixations were located around intersections and that participants were more likely to locate "Stop" signs which were placed at intersections than signs which were located at incongruent locations. This not only shows that participants had learned where to look for "Stop" signs but also demonstrated the importance of scene knowledge in real-world search.

However this scene-knowledge is not intrinsic but needs to be learned. Research has indicated that learner or inexperienced drivers have a reduced spread of search during driving, which has been thought to reflect a lack of knowledge of where to look rather than being a simple issue of cognitive load (Chapman & Underwood, 1998; Underwood, Crundall & Chapman, 2002). Although authors refute a role of memory in visual search (e.g. Horrowitz & Wolfe, 1998; Wolfe et al., 1989) the studies discussed have indicated that cognitive factors are key in deciding where and when to look during search. Hence it is feasible to argue that cognitive distractions are most likely to interfere with those mechanisms of visual search that also require higher-level cognitive processes, thus impacting search behaviour in general.

Pervious research has indicated that working memory representations play a vital role in visual search, however the nature of the interaction between working memory systems and processes guiding visual search are yet to be fully understood. A study by Woodman, Vogel and Luck (2001) revealed that search efficiency did not decrease when working memory capacity was occupied by a concurrent object memory task. This implied that memory for objects and memory for search locations were not being stored in the same working memory subsystem and therefore were not interfering with each other. Furthermore previous work has demonstrated that visual search was slowed when visuospatial working memory was occupied (Woodman & Luck, 2004). Therefore if common mechanisms were used to process both primary and secondary tasks, search efficiency and spatial memory accuracy were impaired. Different models of attention all propose a vital role of working memory in enabling efficient processing of search arrays. Some suggest that a template of the target is stored in visual working memory, which biases perceptual processes to compute items which contain features similar to the target (Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989). Others such as Treisman and colleagues have argued that once an item in the search array was selected by attention, a temporary object file of it is created (Kahneman, Treisman & Gibbs, 1992; Treisman & Sato, 1990; Treisman, 1988). These object files were thought to be identical to the creation of a working memory representation and could therefore be influenced by working memory constraints.

Analysing changes in eye movement behaviour resulting from variations in secondary cognitive load in a simple visual search tasks may reveal which portion of visual search is most affected by distraction. Furthermore if distraction interferes with processes of visual search it could be argued that performance detriments observed in a previous hazard perception task (Savage et al., 2013) were attributable to problems with search behaviour. Furthermore comparing changes to oculomotor metrics resulting from increases in cognitive load between complex (hazard perception) and simple visual search tasks will aid the identification of oculomotor markers of distraction in general.

Individual component processes of secondary cognitive task

An important consideration when examining the effect of cognitive load on the individual component processes of hazard perception performance is the effect of the individual component processes of the secondary task used to manipulate cognitive load. Previous research has manipulated secondary cognitive task demand in driving situations in a wide variety of different ways, including: hands-free and hand-held mobile phone conversations, conversations with a passenger (passenger with or without blindfold), secondary mental arithmetic tasks and secondary peripheral detection tasks. However the processes of listening to, processing and producing verbal information are yet to be isolated and the extent to which their effects on hazard perception performance might differ is yet to be established.

As with breaking down the primary hazard perception task into its individual elements, so too were we interested in reducing the secondary cognitive task to more simplified tasks that reflect mechanisms involved in 1) listening to; 2) producing and 3) processing verbal information. This was achieved by presenting the primary visual hazard perception task along with a secondary wordlist task and manipulating the onset of the wordlist relative to the primary task: 1) by presenting the wordlist task and the hazard perception task concurrently; 2) presenting the wordlist task concurrently with the hazard perception task in the form of an N-back task which requires verbal feedback from the participant; and 3) by presenting the wordlist prior to the hazard perception task and instructing participants to rehearse during the primary task. This methodology allows the processes involved in listening, computing and responding to language to be separated from each other and for their effects on hazard perception performance to be studied in isolation. We argue that these underlying component processes may be similar to those involved in 1) listening to a concurrent conversation; 2) actively engaging in a conversation; and 3) processing the content of a previous conversation, although it is acknowledged that there are many different memory processes involved in listening to and engaging in conversations other than the ones mentioned above.

In driving simulator studies, conversing on a hands-free mobile telephone has been shown to negatively affect primary task performance (Alm & Nillson, 1994). Therefore, although the secondary conversation task could be categorized as being auditory and the driving task primarily visual, these two processes interfered with each other. Alm & Nillson's (1994) experiment simulated conversing on a mobile telephone by instructing participants to perform Baddeley, Logie, Nimmo-Smith and Brereton's (1985) Working Memory Span test on a hands-free mobile telephone. This task is thought to consist of two elements, a working memory and a decision-making component. Drivers were required to listen to statements (such as "archbishops live in factories") and decide whether or not these statements were nonsense. Furthermore participants were required to remember the last five statements that had been presented to them. The primary task (a driving simulation) was either easy or difficult. Subjects were required to navigate through simulated traffic and to react to a sudden onset red square by braking as quickly as possible. Interestingly, the secondary cognitive load manipulations only had an effect on driving performance when the primary driving task was easy. In contrast to expectations, when the primary driving task was difficult RTs to the sudden onset target were not affected. The authors have explained this in terms of resource allocation prioritization: if the primary driving task was easy more attention resources were allocated to the secondary task, thus leading to an increase in RTs in the primary task. However when the primary task was perceived as difficult, drivers devoted more attention to it and therefore performance was not affected.

An important consideration is whether processes of listening to language could be isolated from the cognitive processes involved in holding a conversation. In a simulator study conducted by Strayer & Johnston (2001), participants were required to react to a sudden onset target in their visual field by pressing a button whilst simultaneously performing secondary tasks. Secondary tasks included either listening to the radio or talking to the experimenter on either a hand-held or hands-free device. The purpose of this study was to isolate processes involved in merely listening to language (radio condition), speaking on the telephone (hands-free device) and speaking on the telephone along with physically manipulating the telephone (hand-held condition). In terms of primary task performance deficits, there was no difference between hand-held and hands-free devices. This indicated that the cognitive load associated with conversing rather than the act of physically manipulating the mobile phone was the cause of the increased miss rates. Furthermore the authors demonstrated that listening to the radio or listening to someone read a book did not interfere with RTs or miss rates. These findings suggested that performance deficits observed in the mobile phone condition were not necessarily due to the processes of listening to someone speak but may instead reflect the need to process language.

Memory for conversations has been examined by methods of recognition and recall of prior exchanges. In recall experiments participants were required to record as much information as possible from the conversation in a limited period of time. In recognition studies participants were instructed to choose the original statement amongst distractor statements. Results have demonstrated that recall performance was relatively low: around 10% for immediate recall (Stafford & Daly, 1984) and 8% for delayed recall conditions (Ross & Sicoly, 1979). Participants retained significantly more information in relation to global impressions of the conversation rather than successive changes (Stafford, Burggraf & Sharkey, 1987). This means to say that information seemed to be stored in a gist type fashion rather than in a sequenced list of events. Furthermore, when recognition was utilized to assess memory for conversations, participant's performance was significantly better. One study by MacWhinney, Keenan and Reinke (1982) indicated that participants were able to distinguish between verbatim and paraphrased versions of previous statements after a four-day interval; especially when these statements contained pragmatic or distinctive information. One explanation for the beneficial effects of distinctiveness in memory has been that particularly personal or distinctive information attracted attention thus allowing more in depth processing in comparison to when the information is less distinctive. Memory for conversations can be affected by the perceived importance of the communicated information (Ley, 1978). This study showed a positive relationship between recall performance for conversations if subjects perceived the communication to be of importance. Furthermore, Conway and Bekerian (1987) demonstrated that personal importance of an event was associated with improved recall of that event.

The presented studies demonstrate that memory for conversations are strongly affected by individual differences in perceived importance and personal importance, as well as higher-level cognitive processes such as contextual and semantic memory. Memory for wordlists has been studied extensively in the context of short-term memory (Godden & Baddeley, 1975). Four main findings have been that 1) memory span is inversely related to word length; 2) if words are controlled for by number of syllables and number of phonemes, temporally shorter words are remembered more frequently than longer words; 3) memory span for wordlists can be predicted by the amount of words a subject can read in the space of approximately 2 seconds; and 4) When articulatory processes during the presentation phase were suppressed by instructing participants to utter a irrelevant sounds, word length effects disappeared for visual presentation but persisted in conditions when the stimuli were presented auditorily. These main findings were interpreted within the framework of a phonemically based storage system with a limited capacity. This store was thought to serve as an output buffer for the production of speech and as a supplement to a more general central working memory system (Godden & Baddeley, 1975).

Authors have developed models of working memory as a framework for cognitive research (e.g. Baddeley & Hitch, 1974, Baddeley, 2000). Revised models incorporate a central executive for complex control and decision-making processes along with a variety of subsidiary slave systems argued to be involved in specific processing. The phonological loop is thought to allow the temporal storage of phonological information in speech-based form for up to two seconds. Spoken words such as wordlists presented auditorily are able to enter the phonological store directly; written words however must first be converted. Within the phonological loop, articulatory control processes are thought to act like along the lines of an “inner-voice” rehearsing the information from the phonological store as well as converting visual into phonological information. These articulatory control processes have also been implicated in mechanisms involved in speech production. The visuo-spatial sketchpad, another slave system of the central executive, is thought to process and visual and spatial information. The visuo-spatial sketchpad is thought to play a role in maintaining accurate spatial representations of our surroundings and our place in them (Baddeley, 1997). If two tasks draw upon separate working memory systems no interference is observed in either task. For instance a primary visual task along with a secondary auditory task can be processed without performance detriments in either task. However as working memory capacity is finite, if two tasks utilize the same pool of resources, performance in both tasks should be affected. In dual task situations, information for both tasks needs to be stored and processed simultaneously.

One of the most widely utilized experimental paradigms for studying working memory has been the n-back task (Kirchner, 1958). In this task participants are required to monitor the identity of a series of verbal or nonverbal stimuli and to indicate when the currently presented stimuli matches that stimuli presented n trials previously. A wide range of variations on the n-back task have been utilized in studies examining the neural basis of working memory (Gevins & Cutillo, 1993). The task is thought to involve processes of on-line monitoring, updating and manipulation of the remembered information. Therefore it is assumed that the n-back task places large demands on a number of key processes involved in working memory (Owen et al., 2005). One benefit of the n-back task is that it can be varied to suit the requirements of the current investigation. For instance the number of objects a participant is required to hold in memory can be manipulated to make the task easier or more difficult. Participants can be asked to match the current item with the n^{th} item, which places additional demand on mechanisms of decision making. Alternatively participants can be instructed to merely recall the n^{th} item presented prior to the current one. We argue that this particular variation of the n-back task to some extent isolates working memory components from decision-making, monitoring and response selection mechanisms involved in comparing the current and the n^{th} item. This is due to the fact that subjects were not required to monitor two items and decide whether they were the same but to store one item in memory while processing another (Lezak, 2004).

Although conversing on a mobile telephone requires a large variety of different cognitive sub-processes, we argue that working memory plays a vital role in retaining important information in order to choose an appropriate response. Previous research has attempted to isolate individual components of the larger conversation task such as listening to someone speak (Strayer et al., 2001), contemplating the content of a previous conversation (Savage, Potter & Tatler, 2013) and actively producing language (Alm & Nilsson, 1994). However the extent to which the effect of these individual component processes on hazard perception differ is yet to be determined.

Much like the hazard perception task, we argue that conversing on a mobile phone requires a variety of component sub processes such as, listening, working memory, decision-making and language production. We acknowledge that memory for conversations incorporates a large variety of different types of memory such as semantic and contextual memory. However by examining the effect of the individual component processes (of the more complex conversation task) on hazard perception performance it may be possible to determine which element of conversing on a mobile phone interferes most with hazard perception.

Global and event-related changes in neurophysiology and eye movements during hazard perception

In the majority of prior hazard perception studies a movie was recorded from the driver's point of view and participant's RTs to predefined hazardous stimuli were recorded. Results have typically demonstrated that 1) middle-aged drivers have faster RTs in comparison to young drivers (Quimby & Watts, 1981; McKenna and Crick, 1991); 2) individuals who have been involved in car crashes have longer hazard perception latencies than crash-free individuals (Quimby et al., 1986); 3) RTs on the hazard perception task are inversely correlated with total real-world driving distance (Ahopalo et al., 1987); 4) hazard perception performance can be improved with training (McKenna & Crick, 1997; Deery, 1999); and 5) in a dual task situation, the addition of a secondary mental task increases hazard perception latencies (McKenna & Crick, 1997).

One aspect discussed during the review of the visual search literature was the different mechanisms involved in looking for targets in both target present and absent conditions. Previously it has been argued that hazard perception consisted of at least two separable components: the first is the ability to perceive hazards associated with a situation and the second is the ability to react quickly to a perceived hazard (Sagberg & Bjørnskau, 2006).

We argue that hazard perception involves a similar distinction in terms of target presence and absence as in visual search paradigms. During hazard perception the observer is searching for a target that is either present or absent. Hazards are not present throughout the entire duration of a video but can appear and disappear at any time. Therefore subjects are required to 1) search the driving scene for items that could potentially develop into hazards and to dismiss those which do not; 2) upon locating a potential candidate determine its perceived risk associated with the situation and respond to it as quickly as possible. Previous work has demonstrated that secondary cognitive task demand results in a significant increase in RTs and missing responses to hazardous situations (McKenna & Crick, 1997) and in some cases increased false responses to non hazardous stimuli (Savage et al., 2013). This suggested that increased cognitive task demand was interfering with both processes of rejecting non-hazardous stimuli when no hazards were present and the efficient processing and reaction to hazardous stimuli when these were present. However, this distinction has thus far not been examined explicitly. It could be reasoned that increases in cognitive task demand only affect those processes involved in looking for a hazard but when a target is located, attention resources are focussed on it rather than the secondary cognitive task, thus reducing the effect of distraction.

To explore this argument the period prior to the onset of the hazard in a video (during which subjects are searching for a potential hazard) can be compared to the period when the hazard is visible and on going (and subjects are required to monitor the potential hazard). In this way we would be able to consider whether the effects of secondary cognitive task demand differ depending on the content of the clip. Previous research has identified potential oculomotor and electrophysiological markers of cognitive distraction. We argue that comparing the susceptibility of these markers to variations in cognitive load between periods of hazard presence and absence may demonstrate how each of the two previously discussed processes are affected by secondary cognitive task demand and whether the effects of distraction are upon general behaviour when driving or limited to particular aspects of the complex task.

Savage et al. (2013) assessed the effect of secondary cognitive task demand for the entire duration of the clip. Neurophysiological measures consisted of overall (tonic) differences in frontal and occipital theta, which were recorded for 1-minute intervals and averages were compared across high and low cognitive load trials. Eye movement measures were compared in a similar fashion: averages of individual measures were computed over 1-minute periods and compared between high and low load conditions. However due to the development of more detailed analysis methods including the development of a methodology with which to co-register participant's EEG and eye movement recordings from the hazard perception task, future research will be able to examine overall (tonic) as well as event-related (phasic) changes in oculomotor and neurophysiological measures. The underlying neurophysiological processes of hazard perception are thus far not fully understood. Issues which remain unclear are: 1) what are the differences in fixation related ERPs between high and low cognitive load conditions in complex visual tasks? 2) Does the addition of a secondary cognitive task interfere with preparatory responses prior to the hazard perception task? 3) Does cognitive load affect preparatory periods prior to correct hazard identification? We argue that combining EEG and eye movement recordings in a much more detailed fashion may help answer these questions.

Key Aims of the present thesis

The current thesis consisted of four experiments designed to achieve three main objectives: 1) determining robust signatures of cognitive distraction across a simple visual search task, a basic saccadic task and a complex hazard perception task; 2) isolating and comparing different component processes of secondary cognitive tasks on hazard perception performance; and most importantly 3) determining which individual elements of hazard perception performance are affected by cognitive load. We intended to show that analysing individual elements of saccadic eye movements as well as changes in electrophysiological responses around fixations across simple and complex visual tasks may be of importance in developing meaningful signatures of cognitive distraction in general and not just in driving situations.

Experiment 1 – The effects of cognitive load on processes of alerting, orienting and inhibitory control

To test the hypothesis that secondary cognitive task demand interferes with processes of orienting and inhibitory control, participants completed both a pro and an antisaccade task whilst cognitive load was manipulated by means of a secondary puzzle paradigm. As correct antisaccade performance is thought to reflect effortful suppression of the stimulus driven network, we argue that examining differences between high and low cognitive load conditions would also indicate changes in how resources are allocated by the executive control network. However, previous research suggests that prosaccades are not entirely reflexive but to some extent rely on higher-level cognitive processes (Stuyven et al., 2000; Godijn & Kramer, 2008). Examining to what extent prosaccade performance is susceptible to secondary cognitive task demand may indicate which processes of orienting are affected in the more complex hazard perception task.

Secondary cognitive task demand causes more interference when the primary task is easy (Alm & Nillson's (1994). Therefore we examined the magnitude of interference caused by cognitive load between pro and antisaccade tasks. Both pro and antisaccade tasks are identical in terms of visual load, however task instructions make the antisaccade task much more difficult. If secondary cognitive load has a greater effect when primary task demand is low, we would expect more interference within the prosaccade compared to the antisaccade task.

Having developed a methodology with which to combine oculomotor and electrophysiological recordings, we were able to examine differences in fERPs between high and low cognitive load conditions. This, in combination with the recorded behavioural data demonstrated the effect of secondary cognitive task demand on inhibitory control processes and mechanisms of orienting visual attention to sudden onset targets; both of which are important component processes involved in hazard perception.

Experiment 2 – The effect of cognitive load on visual search performance

Previous research by Gilchrist and Harvey (2006) has demonstrated that visual search may contain a systematic component in that people have a bias for making more horizontal and vertical saccades in comparison to saccades of any other direction. The second study of the present thesis was designed to determine whether secondary cognitive task demand affected principal measures of visual search such as verification times, spread of fixations and percentages of correctly identified targets. Another aim was determining to what extent the systematic component within visual search was susceptible to variations in secondary cognitive task demand.

Experiment 3 – Comparison of the component processes involved in conversing on hazard perception performance

Previous research has demonstrated that conversing on a mobile telephone negatively influenced driving behaviour. This has been shown to be true for hands-free and hand-held devices as well as for contemplating the content of a previous conversation. Conversing on a telephone consists of a variety of different component processes: 1) listening to verbal information, 2) remembering enough from the previous statement to 3) form a cogent response. Experiment three was designed to isolate these individual component processes and compare their effects on hazard perception performance. As it has been demonstrated that memory for real-world conversations was affected by a wide variety of higher-level cognitive as well as personal and individual factors, working memory demand was manipulated by means of wordlists rather than "real" conversations. The relationship between the primary hazard perception and the secondary wordlist task was systematically varied to compare processes of 1) working memory, 2) working memory in combination with language comprehension and 3) working memory in combination with language comprehension and language production.

Experiment 4 – Global and event-related changes in oculomotor and electrophysiological signatures of cognitive task demand in a hazard perception task.

After having examined the effects of secondary cognitive task demand on processes of orienting, inhibitory control and visual search, the final experiment of the present thesis was designed to examine the effects of cognitive load on global and event related changes to our previously identified markers of cognitive distraction within a hazard perception task. Due to the development of more detailed analysis methods we were able to examine not only overall changes in previously identified markers but also demonstrate how events in the primary task affect their susceptibility to cognitive load.

An important consideration for any useful marker of preoccupation is the ability to detect distraction before it manifests itself in an increase in crash risk. The final experimental chapter of this thesis was designed to determine whether previously identified markers of preoccupation were present when the primary hazard perception task was shorter and therefore the period of uncertainty was reduced. We argue that if behavioural measures do not change but eye movements and electrophysiological activity are still affected in the same way by cognitive load as in previous experiments, then these particular metrics may be indicative of distraction in the absence of changes to behaviour. In other words, these metrics may be markers of distraction before the distraction becomes a danger.

Chapter II

The effects of secondary cognitive task demand on processes of orienting, alerting and inhibitory control.

Introduction

The aim of the current study was to determine the effects of secondary cognitive task demand on processes of orienting, alerting and inhibitory control, all of which are vital components of successful hazard perception (e.g., Sagberg & Bjørnskau, 2006). By examining the susceptibility of individual elements of hazard perception to secondary cognitive task demand we intended to determine whether performance detriments in complex video based tasks were potentially caused by interference with processes of orienting, altering and inhibitory control.

One paradigm that has been argued to reflect people's ability to disengage attention at one location and orient it to another is the prosaccade task (see Hutton, 2008 for review). In the standard prosaccade task participants are instructed to direct their gaze towards a sudden onset target as quickly and accurately as possible. Traditionally, the time it takes from the onset of the target to the beginning of the first saccade has been termed latency and is the most common measure in this task. However saccade peak velocities as well as the eye's final landing position relative to the target (gain) are also informative. Prosaccades towards a sudden onset target can be influenced by a wide variety of different cognitive processes resulting from subtly varying task instructions (Mosimann, Felblinger, Colloby & Muri, 2004) to manipulating the time between central cue offset and target onset.

Another well established paradigm of overt visual attention is the antisaccade task. The antisaccade task is comprised of the same visual stimuli as the prosaccade task with altered task instructions. Participants are no longer required to saccade towards the sudden onset target but are instructed to move their eyes to an empty space or placeholder typically in a mirror location from the target. By contrasting natural "reflexive" behaviour (saccading towards the target) with controlled behaviour (the choice to make a saccade in the opposite direction), this surprisingly difficult variation of the prosaccade task is thought to reflect processes of executive function such as inhibitory control, planning and monitoring (Unswort, Engle, & Schrock, 2004; Hutton, 2008). Healthy participants fail to saccade to the opposite placeholder on around 20% of trials, and instead make a false prosaccade towards the sudden onset target followed by a rapid corrective antisaccade towards the correct location (Tatler & Hutton, 2007). It has been argued that the sudden onset of the target produces an automatic motor program for a prosaccade towards the target's location, which needs be inhibited in order for a volitional (endogenous) antisaccade program to be executed. Incorrect prosaccades are produced when the executive processes fail to inhibit or cancel the automatic program. Therefore the execution of a correct antisaccade requires two distinct sub-processes: (1) inhibition of reflexive orienting and (2) volitional control of the saccadic eye movement system (Everling & Fischer, 1998). Measures of most interest in the antisaccade task have generally been the proportion of antisaccade errors, correct antisaccade latencies, error latencies, the time between the first incorrect prosaccade and the following corrective saccade, as well as saccade amplitudes and peak velocities (Hutton, 2008).

As with the prosaccade task there are a wide variety of cognitive processes that have been shown to affect antisaccade task performance, including secondary cognitive load (Mitchell, Macrae & Gilchrist, 2002; Roberts et al., 1994). It was therefore reasoned that the inhibition of the incorrect prosaccade as well as the programming the correct antisaccade required working memory resources.

By varying the temporal relationship between the offset of the central fixation cue and the onset of the target cue it is possible to create both gap and overlap versions of the standard pro- and antisaccade task. The gap version of both tasks traditionally included a 200 ms gap between the disappearance of the central fixation point and the appearance of the target. It has been argued that the disappearance of the central fixation point serves as an alerting signal, which indicates the imminent arrival of the target thus decreasing latencies (Lorenz, Oonk, Barnes, & Hughes, 1995). Therefore successful performance on 200 ms gapped pro- and antisaccade tasks relies on processes of alerting, orienting and inhibitory control. It is proposed that both 200 ms gap pro- and antisaccade tasks combined with a secondary cognitive task demand manipulation may help determine the extent to which processes of orienting, alerting and inhibitory control are affected by cognitive load.

The aim of this current study was to explore the effects of secondary cognitive task demand on three processes crucial to good hazard perception performance: alerting, orienting and inhibitory control. By using these two well established paradigms in combination with Savage’s et al. (2013) secondary cognitive task we considered whether the effects of distraction found in hazard perception paradigms arise due to cognitive load interfering with reflexive orienting, alerting and / or inhibitory control.

In addition to examining changes in traditional pro- and antisaccade measures of latency, gain, peak velocities and response performance the aim of this current study was to determine whether the previously identified oculomotor and electrophysiological markers of cognitive distraction within a complex hazard perception task (Savage et al., 2013) were present in these more visually low-level tasks. Although button press responses are rarely recorded in pro- and antisaccade tasks, in the current study we were interested in whether cognitive load had an effect on the execution of motor responses in such low-level visual tasks. Simulated as well as real-world driving research has shown that RTs increase as a function of secondary cognitive task demand (e.g., Lamble et al, 1999; Horrey & Wickens, 2004). Therefore we were interested in determining whether decrements in RTs may be in part due to interference with processes related motor responses rather than purely cognitive mechanisms.

Oculomotor Consequences of Distraction

Savage et al. (2013) considered whether contemplating a previous conversation led to changes in eye movement metrics during a hazard perception task. Participants were either presented a riddle or a statement directly prior to the beginning of each 1-minute hazard perception clip. Task instructions were to complete the hazard perception task whilst solving the puzzle or remembering the statement. With this secondary task manipulation the authors intended to recreate cognitive processes involved in contemplating a previous conversation and to examine the effects of secondary cognitive task demand on hazard perception performance in the absence of processes relating to active language processing and production. Behavioural results indicated that RTs to hazardous and FRs to non-hazardous stimuli were both significantly increased within the high cognitive task demand condition.

It was argued that the analysis of eye movement metrics might provide a useful diagnostic tool with which to assess a driver's current cognitive state. Analyses of both general fixation patterns and specific elements of the saccadic eye movement system revealed significant changes between high and low cognitive load conditions. General fixation patterns revealed a significant narrowing of the distribution of fixations along the horizontal axis. Closer analyses of individual eye movement metrics revealed a significant increase in saccade peak velocities in the high cognitive load condition. This result was interesting as there was no change in saccade amplitudes as would have been expected given the typically lawful relationship between saccade distance and speed (Abrams, Meyer, & Kornblum, 1989). Research by Di Stasi et al. (2010) indicated that increases in traffic density lead to a significant decrease of saccade peak velocities, which indicates a potential dissociation of the effects of cognitive and visual load on this particular metric. Furthermore results have suggested that saccadic peak velocities decrease as a function of total time on task (Galley, 1993; DiStasi, 2012), which implies that this particular measure may be an indicator of mental or physical fatigue resulting from continued visual activity. However currently it is unclear how fatigue resulting from time on task interacts with secondary cognitive task demand.

Savage et al. (2013) reported a significant increase in blink rates and no changes in blink durations as a result of increased cognitive task demand. Previous research has found that increases in visual task demand are related to shorter blink durations and that cognitive task demand manipulations resulted in increased blink durations and higher rates of blinking (Ahlstrom & Friedman-Berg, 2006; Veltmann & Gaillard, 1996). These findings imply that blink rates and blink durations may provide a useful tool in dissociating between increases in visual and cognitive task demand.

In order to determine whether previously identified markers of cognitive distraction were prevalent in both pro- and antisaccade tasks, oculomotor measures of fixation durations, saccade peak velocities, blink rates, and blink durations were included in the current analyses. Furthermore in addition to RTs measured from the hazard onset, the current study included verification times (VTs), defined as the time between between the final fixation upon the target and the following motor response. This slightly more refined behavioural measure may reflect processes involved in motor response selection or the decision making processes involved in the time from fixating upon an object to deciding it is the correct object to react to.

Neurophysiological consequences of distraction

Savage et al. (2013) investigated the effects of preoccupation on average tonic theta band energy and results suggested that increases in cognitive task demand resulted in an increase in frontal and a decrease in occipital theta band energy measured over the one-minute period. Research in the field of driver distraction has observed increases in phasic frontal theta and beta band power outputs around the time of the hazard onset (Lin et al., 2011). Previous research has also indicated that event related alpha increased in certain circumstances in which subjects were required to withhold or control the execution of a response (Klimesch et al., 1999, Kllimesch, Sauseng, & Hanslmayr, 2007). Therefore in this current experiment we were interested in determining differences between overall theta, beta and alpha band activity between each one-minute block of high or load cognitive load trials as well as differences in these frequency bands around the period of the target onset for both pro- and antisaccade tasks respectively.

As the offset of the central fixation cue 200 ms prior to the onset of the target is thought to act as an alerting cue, this epoch of the pro- and antisaccade task is important in understanding the preparatory responses leading up to the onset of the target. Therefore we were interested in determining differences in ERPs following the alerting cue as well as following target onset between high and low cognitive load conditions for both pro- and antisaccade tasks.

A major advantage of conducting a combined EEG and eye tracking study is the ability to examine differences in *f*ERPs (fixation event related potentials), which has only been made possible relatively recently through the integration of saccade and fixation event codes into the raw EEG data prior to analysis (e.g. Baccino & Manunta, 2005). In this current study fixation and saccade event timings were extracted from the raw eye movement data and merged with the existing stimulus event codes from the experiment. As it had previously been argued that decreases in occipital theta might reflect a reduction in the processing of visual information (Savage et al., 2013), we were interested in determining whether the overall changes in the theta frequency band were reflected by differences in activity of *f*ERPs at cortical sites associated with controlling saccadic eye movements as well as the processing of visual information. These include regions in the cerebral cortex, basal ganglia, thalamus, superior colliculus (SC), brainstem reticular formation and cerebellum (see Munoz & Everling, 2004 for review). As the current study made use of an EEG our analyses were concentrated on cortical sites such as the lateral intraparietal area (LIP) in the posterior parietal cortex (PPC) due to their function as an interface between sensory and motor processing (Andersen, 1997; Colby & Goldberg, 1999), frontal eye fields (FEF) due to their vital role in executing voluntary saccades (Dias & Segraves, 1999; Gaymard et al., 1999), the supplementary eye fields (SEF) due to their involvement in the internally guided decision-making and sequencing of eye movements (Stuphorn, Taylor, & Schall, 2000) and finally the dorsolateral prefrontal cortex (DLPFC) due to its role in executive function, spatial working memory and inhibitory control (Guitton, Buchtel, & Douglas, 1985; Fuster, 1997).

Previous research has shown that correct antisaccade performance may be associated with supplementary eye field as well as frontal lobe activity (Pierrot-Deseilligny et al. 1991; Stuphorn, Taylor, & Schall, 2000) and that increases in executive functions such as working memory and inhibitory control are associated with increased activity in the DLPFC (Corbetta et al, 2008). Therefore the current study was aimed at determining differences in these cortical areas around the time of correct button responses between high and low cognitive task demand conditions for pro- and antisaccade tasks respectively. It is argued that increases in secondary cognitive task demand may result in an increase in DLPFC activity around the time of correct button presses on account of the fact that solving a puzzle whilst simultaneously performing an antisaccade task requires more activation of higher level executive functions such as working memory, problem solving and task switching.

In humans the parietal cortex (PC) has been found to be involved in the motor system as well as the processing and perception of action related information (Fogassi & Luppinio, 2005). Furthermore the PC has been found to play an integral role in the "vision for action" system (Milner & Goodale, 1995, 2004), which has been described as an automatic conversion of visual information into motor commands. Therefore one aim of this current study was to examine differences in activity in these "vision for action" regions of the cortex between high and low cognitive task demand conditions around the time of motor responses.

Method

Design

In this 2 X 2 within-subjects experimental design the independent variables were type of task, which was prosaccade or antisaccade; and cognitive load, which was either low or high (Easy Question = low; Riddle = high). The dependent variables were grouped into three main categories: behavioural, oculomotor and electrophysiological. Behavioural measures consisted of 1) RTs measured from the target onset; 2) VTs measured from the final fixation upon the target; and 3) error rates (pressing the button when fixating upon the false placeholder). Oculomotor measures included 1) first saccade error rates; 2) first saccade latencies; 3) first saccade peak velocities; 4) first saccade gain with respect to target centre; 5) time from initial saccade onset to fixating on target (time to hit); 6) anticipatory eye movements; 7) blink durations; and 8) blink rates. Electrophysiological measures included 1) overall (tonic) mid-theta (4 - 7 Hz Band), alpha (8 - 15 Hz Band) and low-beta (16 - 24 Hz Band) frequency outputs for the entire minute block of either pro or antisaccade trials 2) differences in event-related (phasic) frequency output in response to the target onset; 3) participants grand average (GA) of ERPs 60 ms prior to until 30 ms following correct button presses; and 4) participants GA of *f*ERP in the window 50 ms – 150 ms after each fixation onset.

Participants

15 Participants, 7 male and 8 female, were recruited in and around the University of Dundee by means of the Universities Research Participation System ‘‘SONA’’. All testing was carried out in the Research Wing of the School of Psychology at the University of Dundee. Participation typically lasted around 2 hours and participants were compensated with either course-credit or chocolate. Participants' ages ranged between 18 and 28.

Materials

Participants sat at a table with their heads supported by a chinrest 65 cm away from a 20*"* CRT-Monitor on which the visual stimuli were displayed. Experiment Builder software by SR-Research was used to program the presentation of the audio and visual stimuli. Pro- and antisaccade tasks consisted of a black central fixation box (5 x 5 pixels) and two square placeholders (25 x 25 pixels) situated approximately 7° of visual angle to the left and right of the central fixation box. Subjects were instructed to indicate their responses using response boxes. Participants' eye movements were recorded using an EyeLink1000 eye-tracker. We made use of a variety of different lateral thinking puzzles and quizzes to increase secondary cognitive task demand (including but not limited to “Sloane and MacHale – Lateral Thinking Puzzles”). These questions and riddles were presented via a set of Logitech loudspeakers (See Appendix for list of questions and riddles).

<u>Procedure</u>

200 ms Gap Prosaccade task

In this version of the prosaccade task participants were presented with a central fixation point along with two square placeholders (one left and one right) at the start of each trial. The central fixation point disappeared after a pseudorandom interval (ranging between 500-1000 ms from the start of the trial) and reappeared 200 ms later in either the left (40% of trials) or the right placeholder (40% of trials). The remaining 20% of trials were catch trials in which the words “*Catch Trial*” were displayed for 1500 ms. Presentation order of all trials was intermixed randomly. Participants were required to fixate upon the central fixation point until the target appeared in one of the placeholders. At this point participants were instructed to fixate upon the placeholder containing the target and, having done so, push a button as quickly as possible. A single button was used to indicate the appearance of the target, regardless of which side it appeared on, however, a gaze contingent paradigm was used to determine whether participants were fixating upon the correct placeholder when pressing the button. Each block of prosaccades was programmed to last approximately 1-minute although minor variations naturally occurred due to individual differences in the speed of participants’ performance. Block lengths were chosen in order to match those of previously utilized hazard perception clips (Savage et al., 2013). Each participant completed 14 (1-minute) blocks of prosaccade trials with 7 blocks in the high load condition and 7 blocks in the low load condition. Each 1-minute block comprised 22 experimental trials and 4 catch trials. Trial order in terms of left/right target onset positions as well as high/low load blocks were intermixed randomly.

200 ms Gap Antisaccade task

The procedure of this version of the antisaccade task was the same as with the prosaccade task, with the exception that participants were instructed to fixate upon the opposite placeholder from the one containing the sudden onset target. Each participant completed 14 blocks of 1-minute antisaccade trials with 7 blocks in the high and 7 blocks in the low cognitive load condition. Each 1-minute block comprised 22 experimental trials and 4 catch trials. Presentation order of both 1-minute blocks as well as left/right target onset trials within blocks were intermixed randomly. Trial progressions for both pro and antisaccade tasks can be seen in Figure 1.

Secondary Cognitive Task Demand Manipulation

Prosaccade and antisaccade tasks were presented separately, one after another and not interleaved therefore the order of tasks was varied for each consecutive participant. Participants were instructed to fixate a blank grey screen prior to the beginning of each block of 1-minute pro/antisaccade trials. Secondary cognitive task demand was manipulated by presenting either a simple question (low load e.g. *Q.: "What is the capital of France?" A.: "Paris";* see Appendix) or a riddle (high load e.g. *Q.: "What can pass through water without getting wet?" A.: "Light";* see Appendix) directly prior to the start of each block of 1-minute pro- or antisaccade trials. In both pro- and antisaccade tasks the secondary task instruction were the same. At the end of each 1-minute block there was a brief intermission in which participants were asked to indicate whether they knew the question and whether they had managed to solve it. This information was relevant only for high load questions. If a participant was familiar with a riddle (e.g. had heard it elsewhere) or managed to solve it the subsequent 1-minute block of trials was excluded from our analysis.

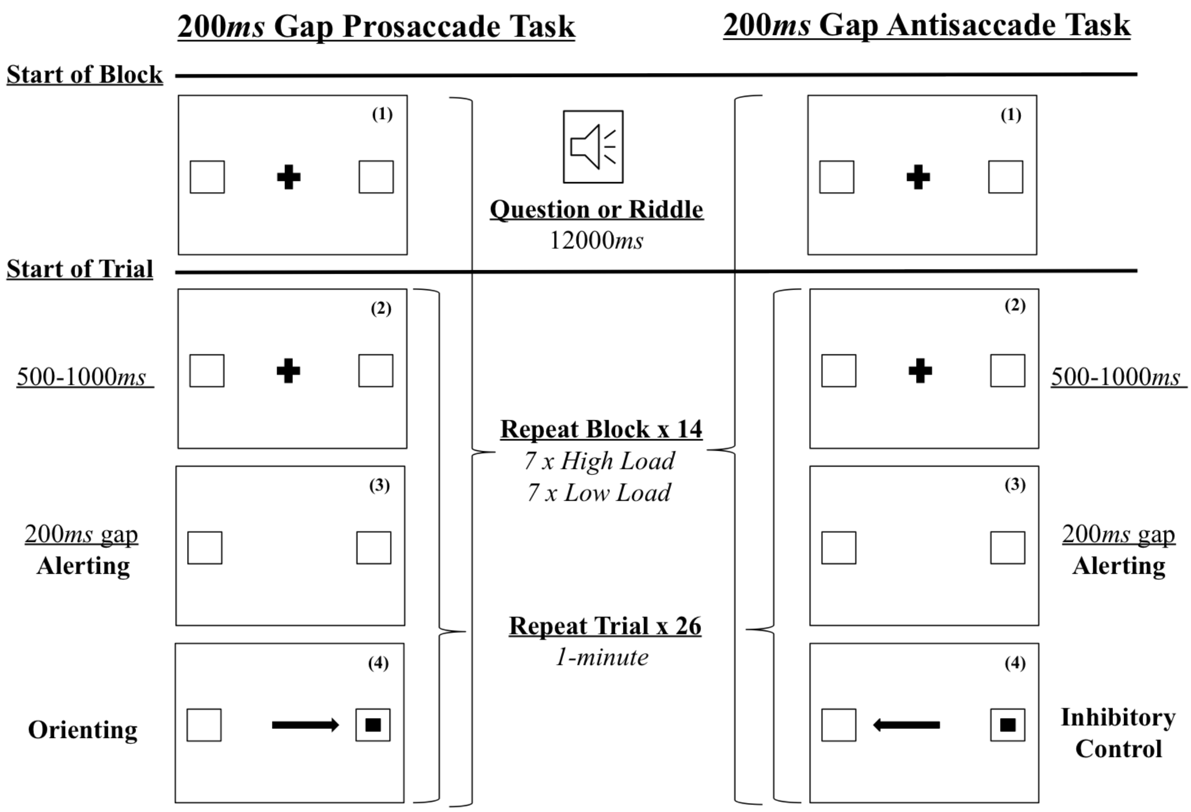


***Figure 1**, Trial progression of both pro and antisaccade tasks. The direction of target in both tasks was varied equally between left and right hand sides of the screen and intermixed randomly. Blocks of high and low cognitive load were intermixed randomly. Prosaccade and Antisaccade tasks were performed separately and presentation order of both tasks was switched for each participants.*

Eye Movement recording

Eye movements were recorded using an SR-Research EyeLink1000 eye-tracker, sampling at 1000 Hz. Each participant completed three brief eye dominance tests prior to the start of testing so that the experimenter was able to track the subject's dominant eye.

A 9-point calibration procedure was used to calibrate the tracker and repeated to validate tracker accuracy. If the validation procedure showed an average error in excess of 0.5° or a maximum error in excess of 1°, the calibration procedure was repeated. Saccades were identified using the standard SR-Research algorithm, which detects saccades when eye position deviates by more than 0.1°, with a minimum velocity of 30 deg s^{-1} and a minimum acceleration of 8000 deg s^{-1}, maintained for at least 4 ms. Data were exported to custom-made MatLab routines for subsequent analysis of saccade, fixation and blink events.

<u>Analyses of Behavioural and Oculomotor Measures using Linear Mixed Models</u>

Data were analysed using Linear Mixed Models (LMMs) using the *lme4* package (version 1.1-7; Bates et al., 2014) in the *R* statistical programming environment (R Development Core Team, 2007). LMMs are particularly well suited to datasets such as those collected in this study for several reasons: 1) they are able to deal with uneven distributions of data between conditions in the design; 2) they can combine continuous and categorical factors within the same model; and 3) they can measure variance across subjects and items simultaneously (Kliegl et al 2012). In constructing models, type of task (pro- or antisaccade) and cognitive load (high or low) were entered as fixed effects whereas subjects, trial number and block number were entered as random effects in all models. For the random effects structure we included the intercept only term for each variable. Where possible the *p*-value was calculated by means of a model comparison. To this effect additional models were constructed in which the fixed effect or interaction for which the *p*-value was to be calculated was removed. The original model and the baseline model were then compared by means of an ANOVA. When *p*-values could not be calculated in this fashion, significance values for differences between conditions were interpreted by means of the *t*-statistic. Given the large amount of observations for each participant the *t*-statistic (i.e. the *Average Effect Size / Standard error*) effectively corresponds to the *z*-statistic (Kliegl et al., 2013). Effects larger than twice their standard errors were interpreted as significant beyond the 5% level (*t*-value => 2).

EEG recording

Stimuli were presented using SR-Research Experiment Builder software; with stimulus event codes simultaneously sent to the EEG and ERP recording system via the TTL parallel output port. Stimulus event codes were used to define each clip as well as its appropriate condition in order to guide later analysis. In order to be able to analyse fixation related potentials as well as EEG activity prior to correct and incorrect responses, the timings of fixation, saccade as well as behavioural events were extracted from the raw data and merged with the stimulus events by means of custom-made MatLab routines. Recordings were carried out using a BioSemi CHA-01 with a digital sampling rate of 2048 Hz. We used 32 electrodes fitted to an elastic cap. Electrodes were placed according to the 10–20 system at scalp sites of Fp1, Fp2, AF3, AF4, F7, F8, F3, F4, Fz, FC1, FC2, FC5, FC6, T7, T8, C3, C4, Cz, CP1, CP2, CP5, CP6, P3, P4, Pz, P7, P8, PO3, PO4, O1, O2, Oz. Additionally, electrodes were positioned above and below the right eye to monitor the timings of vertical eye movements (VEOGs), at the outer canthi of both eyes for horizontal eye movements for later artifact removal and on the left and right mastoids and nose to provide alternative reference sites. Electrode sites were prepared with alcohol to reduce scalp impedances. Sigma conductivity gel was applied to each cap electrode fitting point. After pre-processing, the data were ultimately analysed using BrainVision Analyser software.

EEG Data Processing

In the data pre-processing stage the EEG recordings were down-sampled to the same rate as the eye tracker (1000 Hz) using BDF Decimator82. Recordings were then re-referenced to the linked nose reference site using PolyRex version 1.2 (Kayser & Tenke, 2003). The data were then processed for further analyses with a Butterworth

Zero Phase Filter with low cut-off frequency of 45 Hz and a high cut-off frequency of 0.53 Hz with a time constant of 0.3 and a 48 dB/oct slope. An Ocular Correction Independent Component Analysis (OCICA) was then performed on the whole data using EXG1 re-referenced to EXG2 to identify blink activity and EXG3 re-referenced to EXG4 to identify horizontal eye movement activity. EXG electrodes are individual active electrodes designed to record head and eye movements. Stimulus event codes were then used to further segment the data.

Combining EEG and Eye Movement recordings

In order to analyse *f*ERPs as well as ERPs relating to participants behavioural responses, EEG, oculomotor and behavioural measures were recorded separately and then merged by means of a series of custom developed MatLab routines.

Stimulus event codes pertaining to trial progressions were sent from the display computer via a TTL parallel output port to the laptop that was recording the raw EEG data. Stimulus markers included: start of the experiment, the start of a block (with high or low load identifiers), the beginning of a trial, the disappearance of the central fixation cue, the appearance of the target, the end of the trial, the end of a block and the end of the experiment. Therefore the raw EEG data contained all of the information in terms of when stimuli were being presented as well as which trials were being performed in which conditions. Behavioural event codes pertaining to participant's fixations, saccades, blinks as well as motor responses were not sent in real-time via the parallel output port and therefore needed to be merged post-hoc with the raw EEG data.

To begin with EEG data were down-sampled from the original acquisition rate of 2048 Hz to the same rate as the Eye Tracker (1000 Hz) using BDF Decimator82. The reason for resampling the raw EEG data to the same rate as the eye tracker was that the timings of stimulus event codes were relative to the internal clock of the EEG recording computer (sampling at 2048 Hz) and behavioural event codes were relative to the internal clock of the presentation computer (sampling at 1000 Hz). In order to merge behavioural and stimulus event codes, both sets of markers were required to be in the same time units (1000 Hz). After resampling of the EEG data, stimulus event codes were then exported from BrainVision in form of a text file containing the marker identities as well their onset timings.

Raw eye movement data for each participant were converted from EyeLink's own EDF (Eye Link Data File) into an ASCII (American Standard Code for Information Interchange) text file. These files contained a continuous record of the timings of participants' fixations, saccades, blinks and behavioural input sampled at 1000 Hz (~1 sample per millisecond) relative to the internal clock time of the EyeLink recording system. Custom MatLab scripts were developed to extract and mark relevant behavioural and oculomotor information along with their appropriate on and offset times and to create a continuous recording of these markers.

As the timings of both stimulus and behavioural event codes were relative to the internal clock time of their respective systems, it was necessary to synch both sets of markers relative to the raw EEG data so that merged markers could be imported in BrainVision. This involved creating a continuous record of behavioural event codes relative to the start of the experiment, so that the timing of the first marker, signifying the beginning of the first trial was set to 0 ms. To do so the start trial time of the first trial was subtracted from all other behavioural event code times.

The next step was to synchronise behavioural and stimulus event codes relative to the timings of the EEG recordings. As stimulus event codes were being sent from the EyeLink system directly to the EEG recording system markers signifying the start and end of trials were present in the text file previously exported from *BrainVision*. A second MatLab script was developed to identify the timing of the first trial onset marker (which was relative to the internal clock time of the EEG recording system). In order to synchronise the timings of both sets of markers, the timing of the first trial onset marker (extracted from the stimulus event codes) was added to the timing of each behavioural event code. This had the effect that the continuous timings of behavioural event codes (which were relative to 0) were transformed into the same time reference as the stimulus event codes. Both sets of markers were then merged and sorted by time in ascending order. These continuous records were created for each participant individually and saved in form of a text file, identical in format to the marker file previously exported from BrainVision. These merged marker files were then finally imported back into BrainVision where behavioural event codes were used to further segment the EEG data into periods around fixations as well as correct and incorrect behavioural responses.

EEG Analysis

Stimulus event codes were used to segment the data into high and low cognitive load trials. Trials in which the target appeared on the left were separated from trials in which the target appeared on the right in order to ensure that (any) lateralisation effects did not wash out any significant differences between high and low load conditions. As we were interested in exploring where significant differences between conditions were prevalent, time windows for ERP and *f*ERP analyses were determined in BrainVision by assessing the area of greatest difference between high and low cognitive load conditions. This was achieved using BrainVision's own function to estimate the *t*-values for the differences between two conditions on a sample-by-sample basis. Time windows were chosen to be as large as possible during periods in which *t*-values peaked over +/-2. Grand averages (GAs) for these time windows were exported from BrainVision in the form of a text file. Participants average output for each electrode was analysed between high and low cognitive load conditions in SPSS.

Overall Frequency differences between high and low load conditions

Fast Fourier Transformation (FFT) was performed on the entire one minute block of pro or antisaccade trials using a periodic 10% Hamming Window and a resolution of .03125 Hz. We then averaged the results for each condition and compared overall power in mid-theta (4 - 7 Hz Band), alpha (8 -15 Hz Band) and low-beta (16 – 24 Hz Band) frequency outputs. GAs were created of the total output of each individual frequency band based on the full 1-minute per block recordings for each participant.

Frequency differences around the target onset

Stimulus event codes were used to segment a window 200 ms prior to and 500 ms after the onset of the target. Stimulus event codes were then further used to segment the data into trials in which the target appeared on the left and on the right hand side respectively. Fast Fourier Transformation was performed on each 700 ms window using a 10% Hamming Window and a resolution of 1 Hz. We then averaged the results for each condition and compared overall power output in high-theta (6-10 Hz), high- alpha (12-15 Hz) and low-beta (16-24 Hz) frequency bands. Overall theta, beta and alpha band output was calculated by creating GAs of the total power of each individual frequency based on all 700 ms epochs. GAs were created for each participant and output in the form of a text file for analyses in SPSS.

Differences in activity following alerting signal

Stimulus event codes were used to segment a window 500 ms prior to and 400 ms following the disappearance of the centre fixation cue (altering signal). Stimulus event codes were then further used to segment the data into trials in which the target would appear on the left or on the right hand side respectively After baseline correcting the data based on a window 100 ms after the alerting signal, grand averages (GAs) were created of the area underneath the curve of on-going fluctuation for the window 100 ms prior to the alerting signal.

Differences in activity following the target onset

Stimulus event codes were used to segment a window 200 ms prior to and 450 ms following the target onset. After the data were baseline corrected based on a window 200 ms prior to the target onset GAs were created and differences were analysed between high and low cognitive load conditions.

Differences in activity following correct responses

Behavioural events codes were used to segment a window 60 ms prior to and 30 ms following correct button responses. The segments were first baseline corrected (BC) based on a period 200-100 ms prior to the response before creating GAs to be compared between high and low cognitive load conditions.

Differences in fixation related potentials (fERPs)

Fixation event codes were used to segment a window 200 ms prior to and 500 ms following the onset of each fixation. These segments were first BC based on the 100 ms period leading up to the onset of the fixation before creating GAs based on the window 50-150 ms following each fixation onset in order to determine differences between both high and low cognitive load conditions.

EEG recordings for 4 participants were discarded as a result of a recording error.

Results

Behavioural consequences of preoccupation

We investigated the effect of the type of primary task (pro- or antisaccade), effect of secondary cognitive task demand (high or low) and the interaction of these two variables on reaction times, verification times and overall error rates. A separate

LMM model was run for each variable resulting in three models with five factors each, that is two fixed effects (type of task and cognitive load) as well as three random factors for 1) subjects (the variance contributed by each subjects deviation from the group average) 2) trial number and 3) block number (variance contributed by changes over time).

Trials containing anticipatory eye movements, defined as saccades with first latencies smaller than 50 ms, were discarded and results indicated that RTs were significantly longer in the antisaccade compared to the prosaccade task (b= 88, SE= 3.172, t= 27.741). There was also a main effect of secondary cognitive task demand in that RTs were significantly slower when cognitive load was high (b= 52.1, SE= 3.23, t= 16.14). We found a significant interaction between these two main effects in that the cost of secondary cognitive task demand on participants RTs was greater when executive function in the primary task was low (b= 20.25, SE= 6.34, t= 3.19)

Analyses of VTs indicated a main effect of type of task (b= 17.49, SE= 4.66, t= 3.75) and a significant effect of cognitive task demand (b= 33.04, SE= 4.74, t= 6.97). VTs were significantly longer in the anti compared to the prosaccade task and significantly longer in the high compared to the low cognitive load condition. Furthermore, results suggested a significant interaction between type of task and cognitive load (b= 25.25, SE= 9.32, t= 2.71). This interaction was due to the cost of secondary cognitive task demand being greater in the prosaccade task compared to the antisaccade task.

Button Press performance was significantly lower in the antisaccade compared the prosaccade task (b= 1.98, SE= .22, z= 8.91, p< .001), however there was no main effect of cognitive task demand (b= .43, SE= .23, z= 1.83, p= .066) and no interaction (b= .45, SE= .45, z= .98, p= .32). A summary of behavioural measures for both pro-and antisaccade tasks between high and low cognitive load conditions along with appropriate standard deviations can be seen in Table 1.

Table 1, *Average RTs measured from target onset, Verification Times measured from the final fixation upon the target (in milliseconds) as well as Button Response Performance (% correct trials) along with standard deviations (in parentheses) for pro- and antisaccade tasks between high and low cognitive load conditions.*

	Prosaccade		**Antisaccade**	
	High Load	Low Load	High Load	Low Load
Reaction Times[1, 2, 3]	492 (*233.6*)	434 (*186.86*)	569 (*225.33*)	519 (*191.32*)
Verification Times [1, 2, 3]	281 (*258.05*)	238 (*215.05*)	285 (*256.74*)	257 (*233.75*)
Response Performance [1]	99.09 (*.095*)	99.24 (*.086*)	95.13 (*.215*)	95.07 (*.216*)

1 Denotes a significant difference between pro and antisaccade tasks.
2 Denotes a significant a difference between high and low cognitive load conditions.
3 Denotes a significant interaction between type of task and cognitive load.

Oculomotor consequences of preoccupation

We investigated the effect of the type of primary task (pro or antisaccade), effect of secondary cognitive task demand (high or low) and the interaction of these two variables on 1) first saccade performance 2) first saccade latency 3) first saccade peak velocity 4) first saccade gain 5) time to hit 6) anticipatory errors 7) blink durations and 8) blink rates. A separate LMM model was tested for each variable resulting in eight models with five factors each: two fixed effects (executive function and cognitive load) as well as three random factors for 1) subjects (the variance contributed by each subjects deviation from the group average) 2) trial number and 3) block number (variance contributed by changes over time). A summary of all oculomotor measures for both pro- and antisaccade tasks between high and low cognitive load conditions along with their standard deviations can be seen in Table 2.

If participants' first eye movement was in the wrong direction (depending on the task: toward or away from the target), it was counted as a first saccade error. First saccade performance rates were significantly lower in the antisaccade compared to the prosaccade task (b= 2.25, SE= .095, z= 23.76, p< .001) as well as lower in the high compared to the low cognitive load condition (b= .19, SE= .093, z= 2.07, p= .038), however results indicated no interaction between cognitive load and type of task.

First saccade latencies were significantly longer in the antisaccade compared to the prosaccade task (b= 77.29, SE= 1.4, t= 55.14). Participants were also significantly slower in the high compared to the low cognitive task demand condition (b= 3.91, SE= 1.39, t= 2.82), however results indicated no interaction between cognitive load and type of task.

First saccade peak velocities were significantly slower in the antisaccade compared to the prosaccade task (b= 21.77, SE= 2.08, t= 10.45) however there was no effect of cognitive load (b= 2.77, SE= 2.1, t= 1.32) and no interaction.

First saccade gain was found to be significantly lower in the antisaccade compared to the prosaccade task (b= 3.8, SE= .34, t= 11.41) and significantly lower in the high as compared to the low cognitive task demand condition (b= .99, SE= .33, t= 2.99). Results indicated no interaction between cognitive load and type of task.

Time to hit the target was significantly longer in the antisaccade compared to the prosaccade task (b= 73.8, SE= 4.01, t= 18.41) and significantly slower in the high compared to the low cognitive task demand condition (b= 20.37, SE= 4.06, t= 5.02) with no interaction between type of task and cognitive load.

Anticipatory errors were significantly more frequent in the prosaccade compared to the antisaccade task (b= 2.38, SE= .43, t= 5.61) but there was no effect of cognitive load (b= .31, SE= .43, t= 0.72). Results indicated a significant interaction between the two main factors of this model (b= 1.74, SE= .85, t= 2.05).

Analysis of blink rates and blink durations was restricted to the inter trial period as all trials containing blinks were discarded. Results indicate that blink durations were significantly increased in the antisaccade compared to the prosaccade task (b= 16.79, SE= 4.24, t= 3.96) however no effect of cognitive task demand was found (b= 5.5, SE= 4.45, t= 1.24). There was a significant interaction between executive and cognitive task demand manipulations (b= 5.5, SE= 4.45, t= 1.24). This interaction arises due to a dissociation of the effects of cognitive load on anticipatory errors between pro- and antisaccade tasks. In the prosaccade task anticipatory errors were higher in the high cognitive load condition, whereas in the antisaccade task anticipatory errors were higher in the low cognitive load condition.

There was no significant main effect of type of task (b= 0.09, SE= 1.29, t= .07) or cognitive load (b= 1.4, SE= 1.29, t= 1.08) on blink rates as well as no interaction between type of task and cognitive load. Increased cognitive load resulted in an increase in blink rates, however this trend was not significant.

Table 2, *Average First Saccade Performance (FSP - % correct), First Saccade latency (FSL - in milliseconds), First saccade peak velocity (in degrees/second), Mean saccade duration (in milliseconds), Gain with respect to target centre (target location/saccade end position), Time to Hit (in milliseconds), Anticipatory Error rates (in %), Blink durations (in milliseconds) and Blink Rates per block along with standard deviations (in parentheses).*

	Prosaccade		**Antisaccade**	
	High Load	Low Load	High Load	Low Load
FSP [1, 2]	92.96 (.26)	93.96 (.24)	69.98 (.46)	75.3 (.43)
FSL [1, 2]	146.76 (51.07)	144.82 (42.23)	229.37 (70.16)	223.35 (65.55)
First Saccade Peak Vel [1]	528.96(124.74)	526.52 (120.31)	496.29 (101.71)	504.01 (97.21)
Gain [1, 2]	99.19 (.12)	99.75 (.11)	95.03 (.16)	96.1 (.15)
Time To Hit [1, 2]	213.72 (149.18)	198.97 (136.14)	286.53 (208.43)	265.29 (205.28)
Anticipatory Errors [1, 3]	5.51 (.23)	4.49 (.21)	2.2 (.15)	2.92 (.17)
Blink Durations [1, 3]	97.71 (78.48)	96.55 (100.69	118.69 (118.32)	101.36 (94.54)
Blink Rates	9.25 (10.47)	7.85 (12.14)	9.34 (16.1)	7.48 (12.18)

1 Denotes a significant difference between pro and antisaccade tasks;
2 Denotes a significant difference between high and low cognitive load conditions
3 Denotes a significant interaction between type of task and cognitive load.

Saccade Peak Velocities over time

In order to examine peak velocities over time-on-task, separate LMM were constructed for both pro and antisaccade tasks with cognitive load, trial number and block number as fixed factors and a random factor for subjects. Results indicated that saccade peak velocities decreased significantly over consecutive trials (b= 0.92, SE= 0.28, t= 3.31) as well as blocks (b= 1.38, SE= .51, t= 2.69). Results also indicated a significant three-way interaction between the main factors type of task, cognitive task demand and trial number (b= 2.82, SE= 1.11, t= 2.55) as well as a significant four-way interaction between type of task, cognitive task demand, trial number and block number (b= 0.47, SE= 0.13, t= 3.58). Saccade peak velocities by trial number between both high and low cognitive load conditions can be see in Figure 2 for prosaccades and Figure 3 for antisaccades. Saccade peak velocities by block numbers between both high and low cognitive load conditions can be see in Figure 4 for prosaccades and Figure 5 for antisaccades the shaded regions in all graphs represent 2 standard errors.

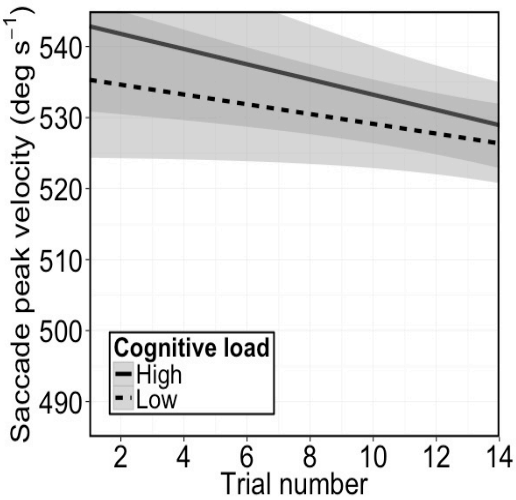


Figure 2, *Average First Saccade Peak Velocities by Trial Number in the prosaccade task between high and low cognitive load conditions*

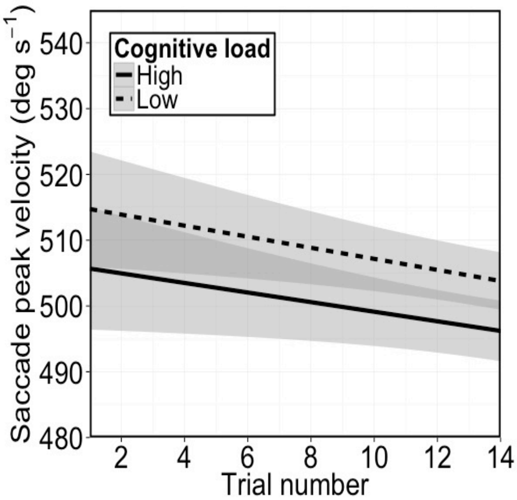


Figure 3*, Average First Saccade Peak Velocities by Trial Number in the antisaccade task between high and low cognitive load conditions*

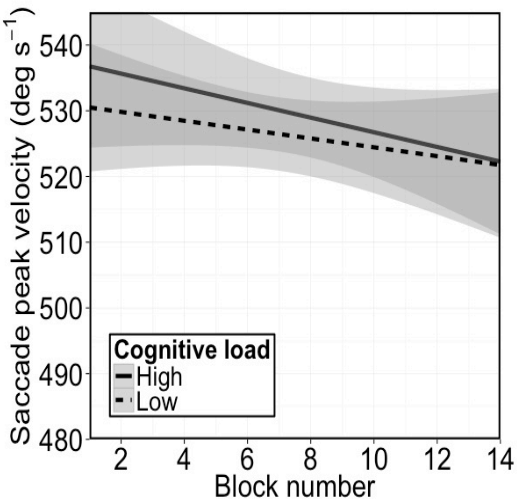


Figure 4*, Average First Saccade Peak Velocities by Block Number in the prosaccade task between high and low cognitive load conditions*

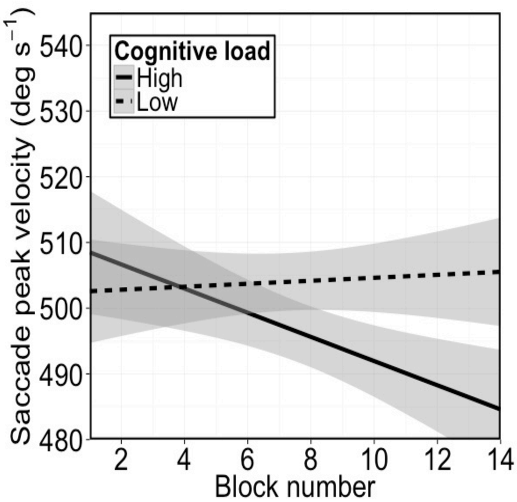


Figure 5*, Average First Saccade Peak Velocities by Block Number in the antisaccade task between high and low cognitive load conditions*

Neurophysiological Results

Overall Frequency differences between conditions

Participants' grand average (GA) of mid-theta (4 – 7 Hz), alpha (8 -15 Hz) and low beta (16 – 24 Hz) frequency outputs were calculated for each electrode individually for both high and low cognitive load conditions for each 1-minute block of pro- and antisaccade trials.

Prosaccade Task

In the prosaccade we found less theta activity at electrode site FC5 in the high compared to the low cognitive task demand condition ($t(10)= 2.5$; $p= .048$). Average tonic theta in the prosaccade task at electrode site FC 5 can be seen between high and low cognitive load conditions in Figure 6**.** Overall alpha activity was significantly lower in the high compared to the low cognitive task demand condition at electrode sites FP1 ($t(10) = 2.46$; $p= .034$); FP2 ($t(10)= 2.63$; p= .025); Fz ($t(10)= 2.82$; $p= .018$): F3 ($t(10)= 3.08$; $p= .012$); F4 ($t(10)= 3.22$; $p= .009$); FC1 ($t(10)= 2.47$; $p= .033$), FC2 ($t(10)= 2.23$; $p= .049$); P3 ($t(10)= 2.32$; $p= .043$); P4 ($t(10)= 2.37$; $p= .039$); P8 ($t(10)= 2.66$; $p= .024$); Oz ($t(10)= 2.72$; $p= .022$); CP6 ($t(10)= 2.99$; $p= .014$) and AF4 ($t(10)= 2.63$; $p= .025$). Average tonic alpha in the prosaccade task at these electrode sites can be seen between high and low cognitive load conditions in Figure 7**.** Furthermore overall low beta was significantly lower in the high compared to the low cognitive task demand condition at electrode sites PO3 ($t(10)= 2.85$; $p= .017$); PO4 ($t(10)= 3.74$; $p= .004$); O1 ($t(10)= 2.45$; $p= .035$), O2 ($t(10)= 2.8$; $p= .019$); Oz ($t(10)= 2.86$; $p= .017$); P4 ($t(10)= 2.36$; $p= .04$); CP2 ($t(10)= 2.32$; $p= .043$); AF4 ($t(10)= 2.54$; $p= .03$); Fz ($t(10)= 2.39$; $p= .038$) and Cz ($t(10)= 2.78$; $p= .02$). Average tonic beta in the prosaccade task at these electrode sites can be seen between high and low cognitive load conditions in Figure 8.

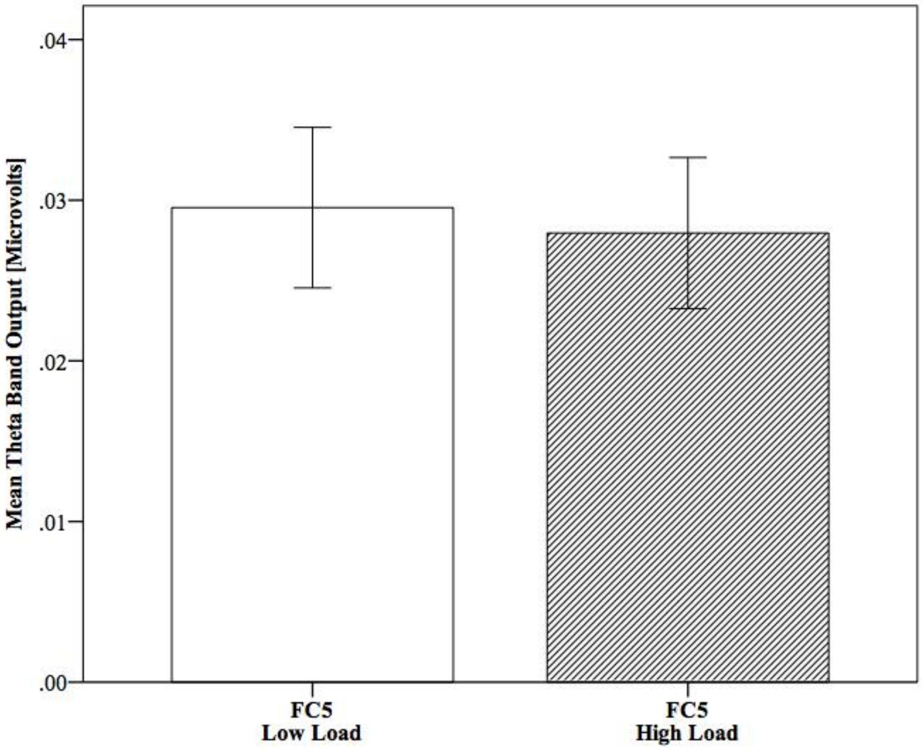


Figure 6, *Average Theta band frequency (4-7 Hz) output in microvolts recorded in the prosaccade task at electrode site FC 5 between high and low cognitive load conditions along with error bars indicating 2 SE.*

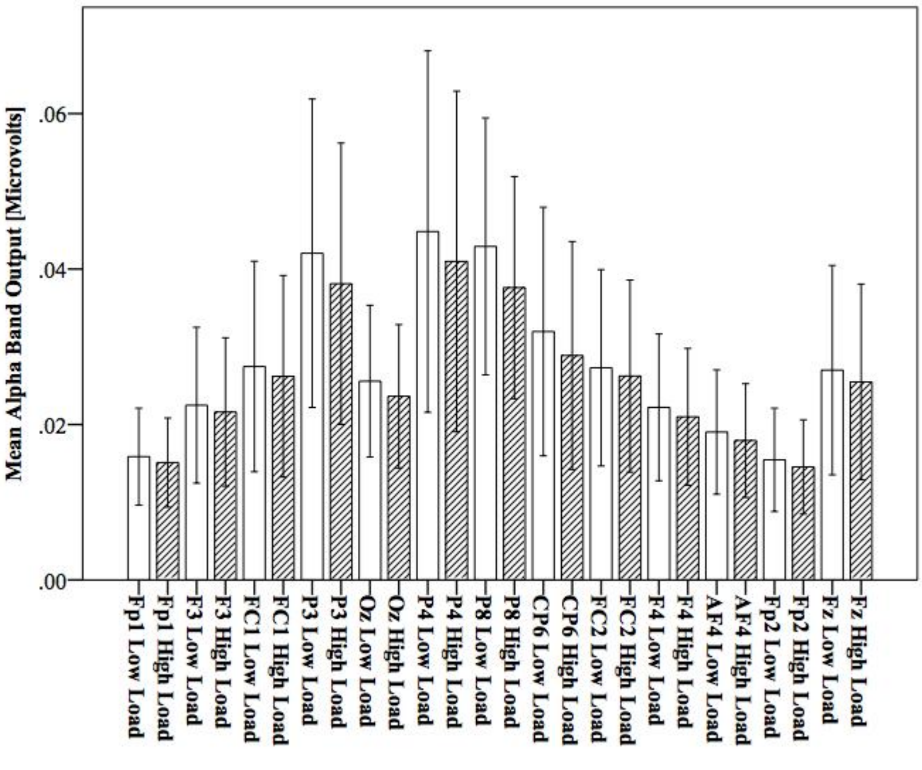


Figure 7, *Average Alpha band frequency (8-15 Hz) output in microvolts recorded in the prosaccade task at electrode sites FP1, F3, FC1, P3, Oz, P4, P8, CP6, FC2, F4, AF4, Fp2 and Fz between high and low cognitive load conditions along with error bars indicating 2 SE.*

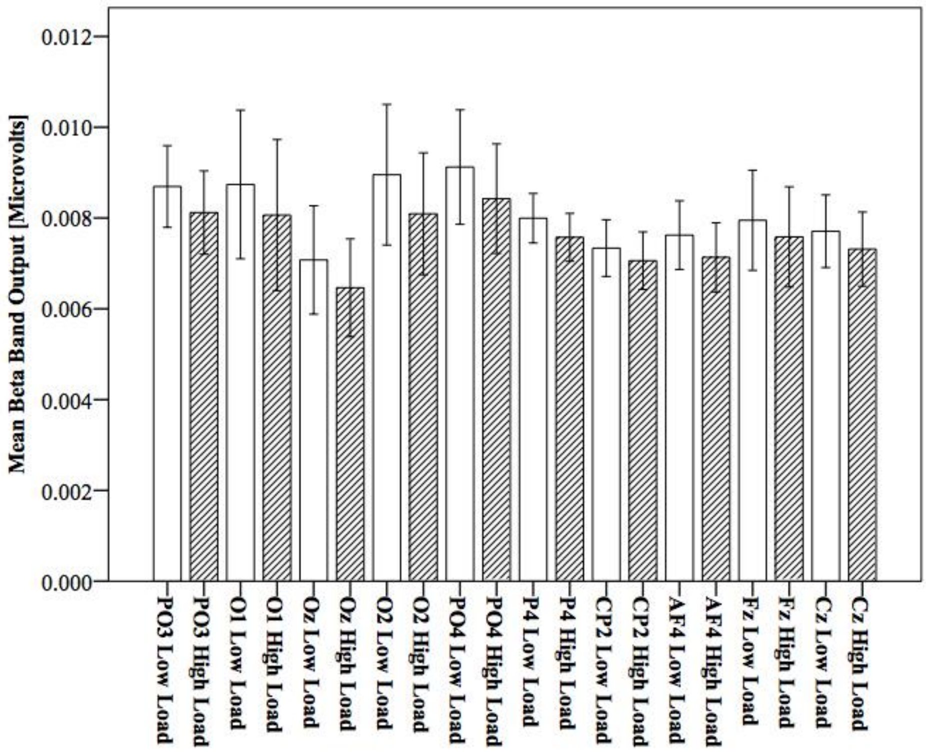


Figure 8, *Average Beta band frequency (16-24 Hz) output in microvolts recorded in the prosaccade task at electrode sites PO3, O1, Oz, O2, PO4, P4, CP2, AF4, Fz and Cz between high and low cognitive load conditions along with error bars indicating 2 SE.*

Frequency differences following target onset

Participants' GAs of high-theta (6-10 Hz), high-alpha (12-15 Hz) and low beta (16 – 24 Hz) frequency outputs were calculated for each electrode individually for both high and low cognitive load conditions for the window 200 ms prior to and 500 ms after the onset of the target. Stimulus event codes were then further used to segment the data into trials in which the target appeared on the left and on the right hand side respectively. First the data were analysed by means of a 2 (high or low cognitive load) x 2 (pro or antisaccade task) x 2 (left or right direction) x 32 (number of electrode sites) repeated measures ANOVA for each frequency band. As activity between electrode-sites are by nature highly inter correlated, and thus Mauchly's test of sphericity was violated, results were interpreted using Greenhouse-Geisser correction.

We found no significant effect of task ($F(1, 10)= 1.97$; $p= .19$), load ($F(1, 10)= .6$; $p= .46$) or direction ($F(1, 10)= .37$; $p= .55$) on average high-theta frequency power following the target onset. Similarly results indicated no effect of task ($F(1, 10)= 1.57$; $p= .24$), load ($F(1, 10)= .77$; $p= .4$) or direction ($F(1, 10)= .09$; $p= .77$) on high-alpha frequency output. The same analyses also revealed no main effect of task ($F(1, 10)= .47$; $p= .51$), load ($F(1, 10)= .02$; $p= .89$) or direction ($F(1, 10)= .3$; $p= .6$) on low-beta frequency output.

Differences in activity following target onset

Participants GAs of activity within the window 30 – 60 ms following the target onset were created and as with the frequency analyses following target onset were analysed by means of a 2x2x2x32 repeated measures ANOVA. There was no significant main effect of task ($F(1, 10)= .15$; $p= .71$) or load ($F(1, 10)= 2.76$; $p= .13$) but results suggested a significant effect of target direction ($F(1, 10)= 11.88$; $p= .006$) on average activity 30 – 60 ms following the target onset, in that GAs of activity over all electrode sites were significantly more positive going when the target appeared on the left as compared to the right hand side of the screen.

Antisaccade Task

In the antisaccade task overall mid theta and low beta frequency activity were not significantly different at any of the 32 electrode sites between high and low cognitive task demand conditions. However results did indicate significantly less overall alpha activity at P8 ($t(10)= 2.25$; $p= .048$). Average tonic alpha in the antisaccade task at electrode site P8 can be seen between high and low cognitive load conditions in Figure 9**.**

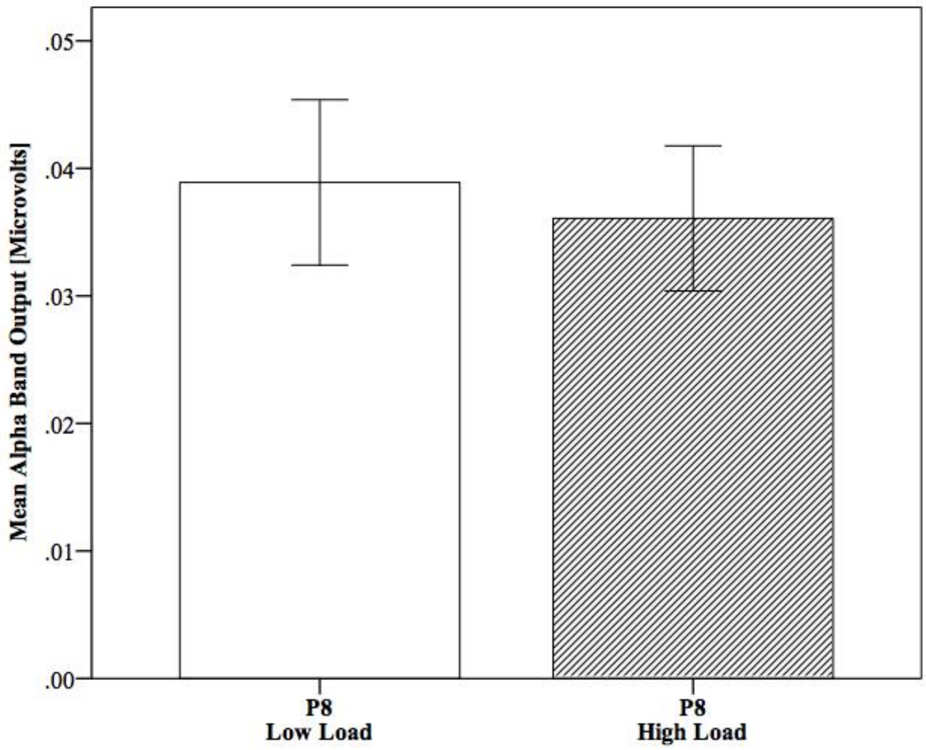


Figure 9, *Average Alpha band frequency (8-15 Hz) output in microvolts recorded in the antisaccade task at electrode site P8 between high and low cognitive load conditions along with error bars indicating 2 SE.*

Differences in activity following alerting signal

Participants GAs of activity within the window 100 ms – 0 ms prior to the onset of the alerting signal were created and as with the frequency analyses following target onset and ERP analyses following target onset, the data were submitted to a 2x2x2x32 repeated measures ANOVA. There was no significant main effect of task ($F(1, 10)$= .023; p= .88), load ($F(1, 10)$= 1.31; p= .28) or direction ($F(1, 10)$= .028; p= .87) on average activity 100 ms prior to the alerting signal.

Differences in activity after correct responses

False responses in the pro and antisaccade tasks were scored if the subject was fixating in the inappropriate location when pressing the button. Activity following false button press responses was not calculated due to participants making too few errors in the prosaccade task. After stimulus event codes and behavioural event codes were used to segment windows 500 ms prior to and 1000 ms after correct response, GAs were created for the epoch 60 ms prior to and 30 ms following correct responses.

Prosaccade Task

In the prosaccade task we found significantly more negative going activity in the low compared to the high cognitive task demand condition at electrode sites P3 ($t(10)= -2.47$; $p= .033$); PO3 ($t(10)= -2.36$; $p= .041$); PO4 ($t(10)= -2.83$; $p= .018$); P4 ($t(10)= -3.28$; $p= .008$) and CP6 ($t(10)= -2.3$; $p= .044$). Grand average waveforms recorded in the prosaccade task at these electrode sites can be seen for both high and low cognitive load conditions along with a difference map plotting the cortical location of these differences in Figure 10.

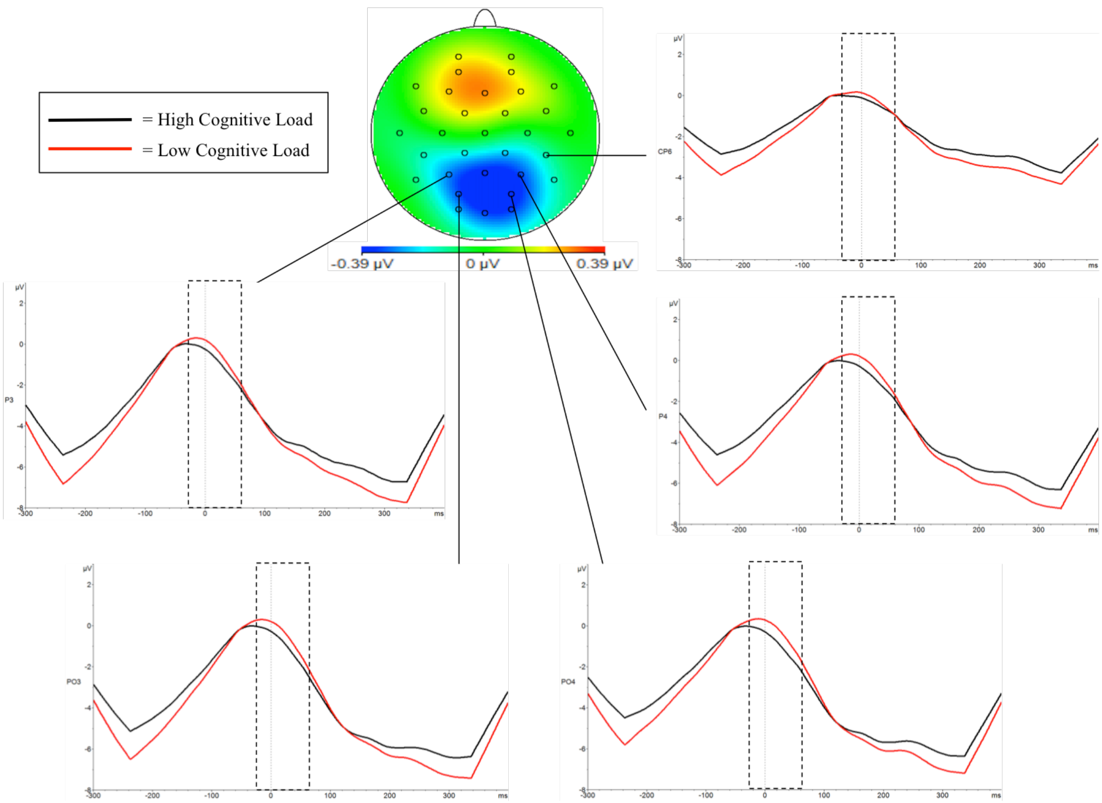


Figure 10, *Grand average difference waveforms at CP6, P4, PO4, PO3 and P3 along with average difference map. Differences between conditions were calculated in the highlighted area 30 ms prior to until 60 ms following correct button responses.*

Antisaccade Task

Conversely in the antisaccade task average activity was significantly more positive going in the low compared to the high cognitive task demand condition at electrode sites FP1 ($t(10)= 2.38$; $p= .038$); F7 ($t(10)= 2.89$; $p= .016$); T8 ($t(10)= 2.44$; $p= .035$) and F4 ($t(10)= 2.54$; $p= .03$). Furthermore we found marginally more negative going activity in the high compared to the low cognitive task demand condition at F3 ($t(10)= 2.22$; $p= .051$). Grand average waveforms recorded in the antisaccade task at these electrode sites can be seen for both high and low cognitive load conditions along with a difference map plotting the cortical location of these differences in Figure 11.

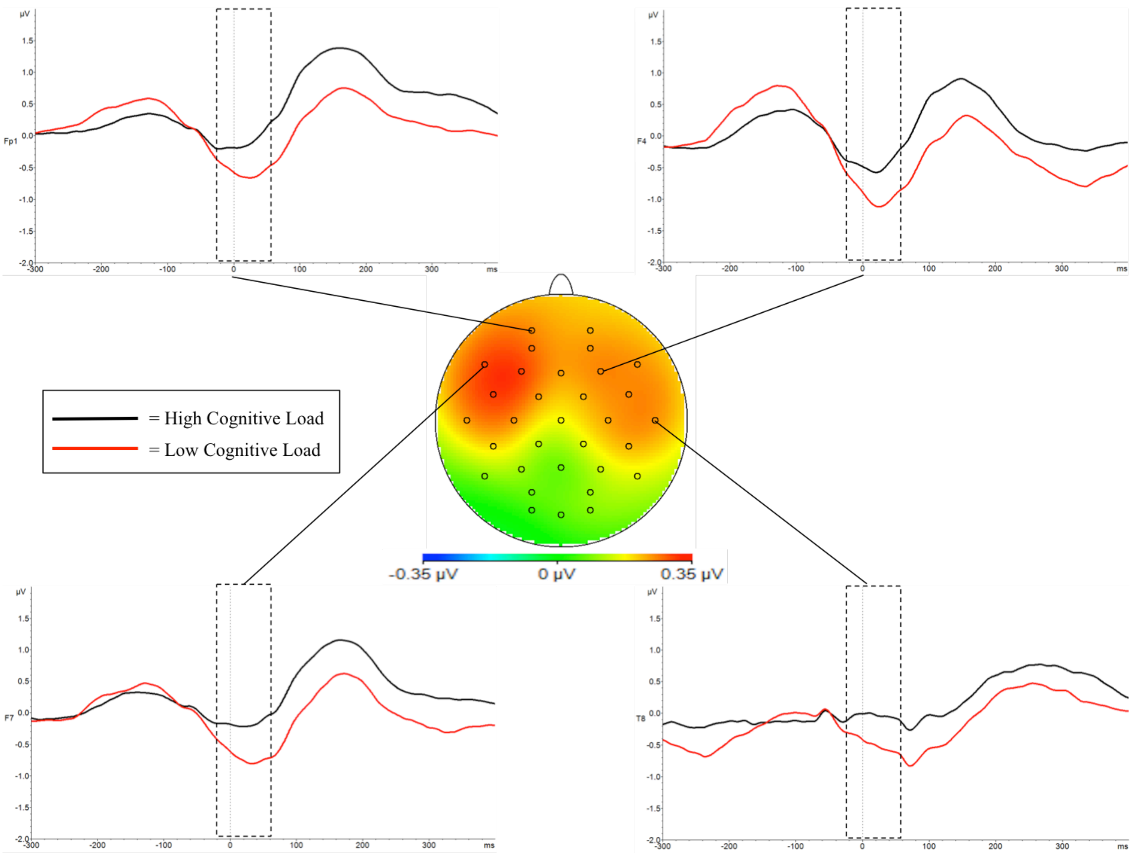


Figure 11, *Grand average difference waveforms recorded in the antisaccade tasks at FP1, FP2, F7 and T8 along with difference map. Differences between conditions were calculated in the highlighted area 30 ms prior to until 60 ms following correct button responses.*

Differences in fixation related potentials (fERPs)

After fixation event codes were used to segment windows 150 ms prior to and 600 ms following fixations, GAs were created for the epoch 50–150 ms after each fixation onset.

Prosaccade Task

In the prosaccade task average activity was significantly more positive going in the high compared to the low cognitive task demand condition at electrode sites C3 ($t(10)= -3.82$; $p= .003$); CP1 ($t(10)= 2.77$; $p= .02$); CP5 ($t(10)= -2.58$; $p= .028$); P3 ($t(10)= -2.44$; $p= .035$) and Cz ($t(10)= -2.62$; $p= .026$). Grand average waveforms for *f*ERPs recorded in the antisaccade task at these electrode sites can be seen for both high and low cognitive load conditions along with a difference map plotting the cortical location of these differences in Figure 12.

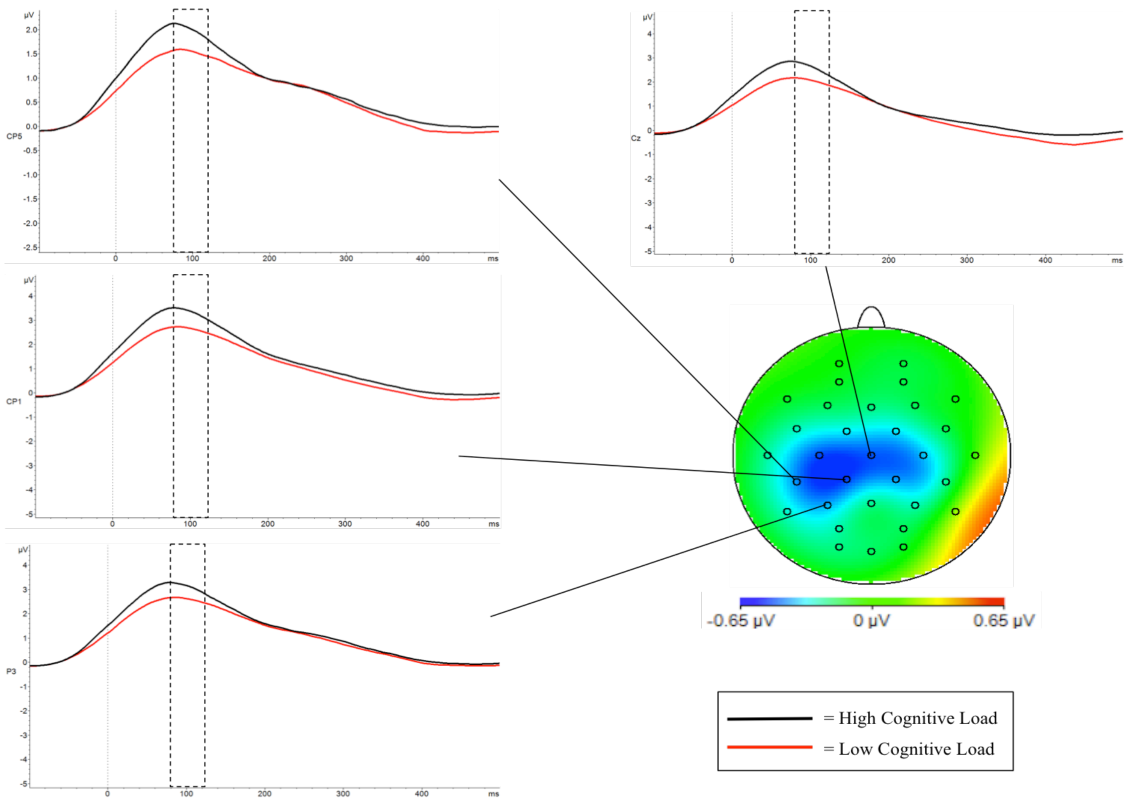


Figure 12, *Grand average difference waveforms of fERPs recorded in the prosaccade tasks at CP5, CP1, P3 and Cz along with difference map. Differences between conditions were calculated in the highlighted area 50-150 ms following fixation onsets which are highlighted at 0 ms.*

Antisaccade Task

In the antisaccade task average activity of *f*ERPs was more negative going in the high compared to the low cognitive task demand condition at electrode sites FP1 ($t(10)$= 2.45; p= .034): F3 ($t(10)$= 2.23; p= .05): F4 ($t(10)$= 2.51; p= .031); FP2 ($t(10)$= 2.69; p= .023) and Fz ($t(10)$= 2.69; p= .023). Grand average waveforms for *f*ERPs recorded in the antisaccade task at these electrode sites can be seen for both high and low cognitive load conditions along with a difference map plotting the cortical location of these differences in Figure 13.

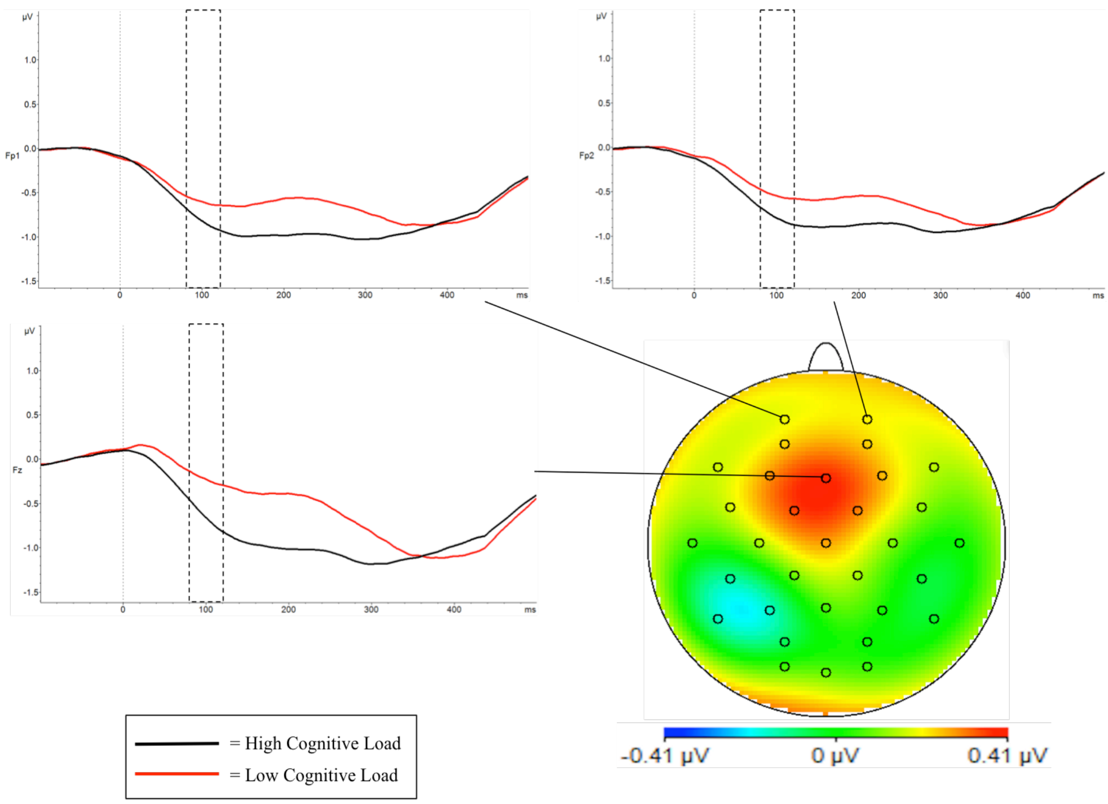


Figure 13, *Grand average difference waveforms of fERPs recorded in the antisaccade task at FP1, FP2 and Fz along with difference map. Differences between conditions were calculated in the highlighted area 50-150 ms following fixation onsets which are highlighted at 0 ms.*

Discussion

Previous research has indicated that contemplating a previously presented riddle has detrimental effects on behavioural, oculomotor and electrophysiological measures within a hazard perception task (Savage et al., 2013). The first experiment of this current thesis was designed to test whether previously observed decrements in hazard perception performance could in part be due to variations in cognitive load interfering with processes of alerting, orienting and inhibitory control. Therefore we examined the effects of thinking about a recently heard puzzle on participants' behavioural, eye movement and neurophysiological metrics within both prosaccade and antisaccade tasks. After hearing a puzzle, participants were slower to make a manual button response measured both from the target onset (RT) and the final fixation upon the target (VT) in both pro and antisaccade tasks. The cost to both RTs and VTs associated with increased secondary cognitive load was greater when the primary task was easy (within the prosaccade task) compared to when it was difficult (antisaccade task). Overall button press response performance was affected by the type of task (pro / antisaccade) but not by cognitive load. Furthermore high cognitive load was associated with significantly reduced gain, increased first saccade error rates and blink durations within both pro- and antisaccade tasks. The current study indicated that increased cognitive load resulted in changes to eye movement measures in simple reflexive (prosaccade) and inhibitory control (antisaccade) responses. Electrophysiological data revealed differences in ERPs around motor responses, tonic as well as phasic frequency band outputs between high and low cognitive load conditions and pro- and antisaccade tasks. The co-registration of eye tracking and EEG data demonstrated significant differences in *f*ERPs both between high and low cognitive load conditions as well as between pro and antisaccade tasks. Findings from this current study suggested that secondary cognitive task demand was interfering with processes of alerting, orienting and inhibitory control. Furthermore high cognitive load resulted in characteristic changes in eye movement behaviour that were similar to those observed in complex video based tasks.

Behavioural Consequences of preoccupation

RTs are not a typical measure of pro/antisaccade performance, however we were interested in including these because 1) we were interested in determining the behavioural consequences of preoccupation and 2) we argue that the efficiency and speed of our cognitive processing may be reflected in our motor output. The two RT measures utilized for this were the RT from target-onset and the RT from the final fixation upon the hazard (VT). Overall RT is a composite measure of first latency, first saccade errors, time to hit and VT. We argue that RTs reflect our overall processing throughout the entire trial whereas VTs reflect the decision-making processes involved from the point of landing upon a target to deciding it requires a response as well as the speed of motor planning and execution components (e.g., Just & Carpenter, 1979).

We found that an increase in cognitive task demand resulted in a significant increase in RTs and VTs for both pro and antisaccade tasks, but did not interfere with overall button response performance. There was a significant interaction between type of task and cognitive load on both measures of RTs and VTs. This interaction resulted from the effect of secondary cognitive load on participants' RTs and VTs being greater in the prosaccade compared to the antisaccade task. The cost of contemplating a previously heard puzzle on RTs was approximately 60 ms in the prosaccade and 50 ms in the antisaccade task. The cost of cognitive load on VTs was 50 ms in the pro compared to only 24 ms for the antisaccade task. These results indicated that the effect of cognitive task demand on RTs was greatest when the primary task was easy. As VTs were more susceptible to increases in cognitive load than RTs, it could be reasoned that the increase in overall RTs may be in part due to the slowing down of the decision making as well as motor planning and execution processes involved from the point of fixating upon a target to deciding it is the appropriate target.

Participants made significantly more button presses whilst fixating in the wrong placeholder (false response) in the anti- compared to the prosaccade task, however there was no effect of cognitive task demand. This implies that although participants failed significantly more often in looking at the correct placeholder and pressing the button in the anti- compared to the prosaccade task, this performance detriment was not accentuated by an increase in cognitive task demand. As RTs and VTs were longer in the high compared to the low cognitive task demand condition, we argue that cognitive distraction resulted in a reduction in the speed of primary task processing but did not interfere with overall processing efficiency.

Taken together, these behavioural results suggested that when cognitive task demand was high participants were significantly slower but no less accurate in responding to sudden onset targets. Furthermore, changes in RT measures indicated that the effect of increased cognitive task demand was greatest when the primary task was easy (within the prosaccade task). This indicates that when processes relating to executive function in the primary task were high, the effects of secondary cognitive load were attenuated. This interaction is in line with models of executive control of attention (e.g. Corbetta, Patel, & Schulman, 2008; Wickens, 2008): if primary task processing occupies the majority of attention resources, the intrusion of task irrelevant information can be down-regulated in order to prevent undesired orienting (overt or covert) away from the primary task. In simulated driving studies it has been demonstrated that manipulations in secondary cognitive task demand resulted in an increase in RTs only when the primary driving task was easy (Alm & Nillson, 1994). It has been argued that the antisaccade task requires increased activity in networks associated with executive functions in order to inhibit erroneous prosaccades and to plan correct antisaccades (Evdokimidis et al., 1996; Everling et al., 1997**)**. As the antisaccade task requires more cognitive resources to compute than the prosaccade task, these resources are no longer available to appropriately process the secondary task, thus attenuating the effects of distraction. When primary task demand is easy (i.e. in the prosaccade task) processes relating to executive function are available to compute the secondary task, therefore the effect of distraction was larger because more resources were being occupied by solving the puzzle.

Oculomotor Signatures of preoccupation

We considered measures of pro- and antisaccade performance, focussing in detail on the first saccadic responses (their latencies, direction, gain and peak velocities). We also considered the frequency with which saccades were launched in anticipation of (rather than in response to) the onset of the peripheral target.

Differences between pro and antisaccade tasks

First saccade latency describes the interval between the target onset and the initiation of the first saccade. As such this metric has typically been taken to reflect how quickly saccade programs are executed. Unsurprisingly our results suggested a significant increase in first saccade latencies in the anti- compared to the prosaccade task. Previous research has demonstrated that latencies of endogenously cued saccades (antisaccades) are significantly longer than those of exogenously cued saccades (prosaccades; e.g., Walker, Walker, Husain & Kennard, 2000). It has been argued that this difference in latency is due to the fact that the inhibitory processes involved in supressing the erroneous prosaccade are effortful and time consuming (Hutton, 2008). As in antisaccade tasks healthy participants usually fail to direct their eyes towards the opposite placeholder with their first saccade on around 20% of trials (e.g. Fischer & Weber, 1992; Smyrnis et al., 2002), it was perhaps not surprising that first saccade error rates were significantly higher in anti- compared to the prosaccade task. Erroneous saccades in the antisaccade task are typically followed by corrective saccades to the appropriate placeholder in the opposite hemi field. In the current study, the time it took for participants to fixate upon the appropriate placeholder (time to hit) was significantly longer in the anti- compared to the prosaccade condition. This is most likely due to a combination of significantly longer first saccade latencies as well as significantly higher first saccade error rates.

Previous research has demonstrated that antisaccades have longer latencies and slower velocities in comparison to prosaccades (Amador et al., 1998; Bell et al., 2000; Munoz and Everling, 2004). In line with this, first saccade peak velocities in the current study were significantly faster in the prosaccade compared to the antisaccade task. It has been argued that a reduction in peak velocities in the antisaccade task is to some extent due to the lack of the presence of a visual stimulus at the saccade end-point (Edelman et al., 2006). In a series of experiments the Edelman and colleagues (2006) demonstrated several factors that influenced peak velocities. For instance, saccades made to a sudden onset target were faster when eye movements were initiated immediately compared to a delay condition. It was reasoned that activation in the visual transient areas of the brain related to eye movements might have endured for a short period after the onset of the target until an immediate saccade was made (Everling et al., 1999), thus enhancing the excitatory drive to brainstem premotor neurons (Edelman & Goldberg, 2001; Ohno et al., 2000). Interestingly Edelman et al. (2006) found that peak velocities of correct ‘immediate’ antisaccades were also faster compared to antisaccades in a condition in which participants were instructed to delay making an immediate eye movement. One possible interpretation has been that the visual transient system was acting as a general arousal or alerting mechanism that was increasing the drive to saccadic neurons in the brainstem, thus increasing peak velocities.

Differences between high and low cognitive load conditions

Increases in cognitive task demand resulted in a significant decrease in first saccade gain. Gain is a ratio metric describing the distance from the target to actual eye landing position (on correct trials): a gain smaller than 1 indicates that saccades were falling short of the target whereas a gain greater than 1 indicates that saccades were overshooting the target. As eye-landing position can only be computed after the target becomes visible, gain has traditionally been argued to reflect the accuracy with which saccade programs were written (e.g., Ettinger et al., 2005). A reduction in first saccade gain therefore may indicate that increased cognitive load was interfering with the computation of the intended fixation position. This reduction in gain was particularly interesting considering that the current study found no significant differences in first saccade peak velocities between high and low cognitive load conditions. This means to say that in the high cognitive load condition although participant's eye movements were the same speed, they were significantly smaller. Given the relationship between saccade peak velocities and amplitudes (e.g. Henriksson et al., 1980; Bahill, Clark, & Stark, 1975), our current results indicated that saccades in the high cognitive load condition were significantly faster than they should be for a saccade of their given amplitude. The direction of the effect of cognitive load on saccade peak velocities is similar to that found by Savage et al. (2013) although the relationship between the individual metrics is different. Interestingly when subjects were allowed to move their eyes freely during a hazard perception task, saccade amplitudes were not affected but peak velocities were increased. In contrast to this when participants were asked to make a saccade of a given size, their peak velocities were maintained but gain was reduced.

Previous research by Unsworth, Schrock and Engle (2004) demonstrated that participants with higher baseline working memory performance exhibited shorter first correct latencies as well as fewer first saccade errors on both pro- and antisaccade tasks. In the current experiment, first saccade latencies were significantly longer in the high compared to the low cognitive load conditions, which seemed to indicate that secondary cognitive task demand was interfering with the efficiency of saccadic programming. This notion was supported by analyses of first saccade error rates. Although overall button response performance was not significantly influenced by secondary cognitive load, first saccade performance was significantly decreased in the high compared to the low cognitive task demand conditions. Taken together these results imply that the addition of a secondary cognitive task interferes with processes of programming eye movements resulting in decrements in both the speed and accuracy of saccades. The fact that first saccade error rates were higher in the high cognitive load condition seems to suggest that secondary cognitive task demand was interfering with processes of inhibitory control required to supress the reflexive erroneous prosaccade in favour of planning a voluntary antisaccade. Interestingly, increased secondary cognitive load also resulted in increased first saccade error rates in the prosaccade task. This indicated that variations in secondary cognitive task demand not only interfered with processes of inhibitory control (antisaccade task) but also lead to differences in the directing of the focus of attention. Therefore it seems that processes relating to working memory play a role in the generation of volitional- and the suppression of reflexive eye movements.

Time to hit is the time it takes people to fixate upon the target for the first time (measured from the target onset) and is therefore a composite measure of first saccade latencies in addition to any necessary correction latencies. Participants were significantly slower to fixate upon the target in the high compared to the low cognitive load condition. This was most likely a result of increases in first saccade latencies as well as a significantly larger first saccade error rate in the high as compared to the low cognitive load condition.

Taken together, eye movement metrics recorded in this current study indicated that an increase in secondary cognitive load was interfering with processes of orienting (increased first saccade error rate in the prosaccade task), alerting (increased first saccade latencies in both tasks) and inhibitory control (increased first saccade error rates in the antisaccade task).

Blink Rates and Durations

Savage et al. (2013) considered the effects of preoccupation on participants' blink rates and durations and found that whereas blink rates increased as a consequence of variations in secondary cognitive task demand, blink durations were unchanged. Different elements of blinks have been thought to be indicators of both fatigue and mental workload (Benedetto et al., 2011; Recarte et al., 2008; Veltman & Gaillard, 1996). In the current study blink durations were significantly longer both as a result of increased cognitive task demand as well as in the anti- compared to the prosaccade task. There was also a significant interaction between cognitive task demand and type of task, which was due to the fact that blink durations were longest when both processes relating to executive function and cognitive load were high (antisaccade task / high load condition). Regarding average blink durations it becomes clear that the effect of cognitive task demand alone has only a very small effect on this particular metric. Blink durations in the prosaccade task increased by merely a millisecond as a result of increasing cognitive task demand. Furthermore blink durations in the 'antisaccade task / low cognitive load' condition were only 4 ms longer than in the 'prosaccade / high cognitive load' condition. However, when cognitive load and processes relating to executive function were both high, blink durations were increased by over 20 ms. This interaction indicated that, on its own, the effect of cognitive task demand did not necessarily substantially affect blink durations. It was when both processes relating to executive function and cognitive load were high that the largest effect on blink durations was recorded.

Analysis of blink rates revealed no significant changes relating to either the type of task or cognitive load. This was most likely, to some extent, due to the high standard error rates in both conditions, indicating a large amount of variation in blink rates across participants. Interestingly, it seems that participants were making on average two more blinks when cognitive load was high than when it was low. Most interestingly was that average blink rates were the same for both pro- and antisaccade tasks. This means to say that in the 'prosaccade / high cognitive load' condition participants were making on average the same amount of blinks as in the 'antisaccade / high cognitive load' condition. The same is true for 'prosaccade / low cognitive load' and 'antisaccade / low cognitive load' conditions. Although this result was not significant the trend indicated that blink rates were influenced only by increases in cognitive task demand and not by variations in processes relating to executive function. One likely explanation for not finding a significant increase in blink rates in this low level task was that the highly structured trial progression might have lead to subjects to supress blinks during the short duration of the actual trial in order to blink as soon as they had pressed the button bringing the trial to an end. Nevertheless the dissociation of effects on blink rates and durations is an interesting one as it may indicate that these measures could be used to determine variations in primary as well as secondary cognitive task demand.

Saccade Peak Velocities over time

Saccade peak velocities got progressively slower over trials, most likely indicating a fatigue effect (DiSasi et al., 2010). Interestingly the current study indicated a significant interaction between type of task and cognitive load on the rate at which saccade peak velocities decreased. Saccade peak velocities decreased fastest when both processes relating to executive function and cognitive load were high (antisaccade / high load) compared to all other conditions. One possible explanation of this decrease in saccade peak velocities was a natural fatiguing of the oculomotor muscles over time due to the repetitiveness of the task (Galley, 1993; DiStasi, 2012). This would also account for the faster decline in the antisaccade task as more corrective eye movements means more eye movements in the same amount of time which equates to more demands on the oculomotor muscles. However, if the slowing down of saccade peak velocities was purely due to the natural fatiguing of the oculomotor muscles one would expect no difference between 1) high and low cognitive load conditions and 2) no interaction between the type of task and cognitive load. Therefore this result indicated that saccade peak velocities were affected by both biological and cognitive factors. Another interesting observation was that during the prosaccade task peak velocities were faster at the start of the experiment in the high compared to the low cognitive load condition. However by the conclusion of the experiment this pattern was reversed. This was due to the fact that peak velocities decreased faster in the high compared to the low cognitive load condition. Furthermore, when both processes relating to executive functions and cognitive load were high, peak velocities were at their slowest and decreased fastest. These results indicated that peak velocities decreased not only as a function of time on task but also interacted with both cognitive load and type of task. The pattern of results suggested that when cognitive load was high, peak velocities were increased but that the increase in cognitive load also resulted in a faster decline in velocities over time. This could potentially be explained within a (de)-activation account of saccadic peak velocities in that increased activity results in increased peak velocities (App & Debus, 1998).

However high cognitive load over time also may have resulted in a faster deterioration of mental activity, which was in turn reflected in the faster decrease in peak velocities.

<u>*Electrophysiological Consequences of Preoccupation*</u>

Effects of distraction on event related measures in the prosaccade task

Results from the prosaccade task indicated that the average activity of *f*ERPs was significantly greater in the high compared to the low cognitive task demand condition at central and left parietal sites. The lateral intraparietal cortex (LIP) in the posterior parietal cortex has been implicated in the interface between sensory and motor processing (Andersen, 1997; Colby & Goldberg, 1999) but has also been found to project to the intermediate layers of the SC (Paré & Wurtz, 2001) and the frontal cortical oculomotor areas such as the FEF, SEF and DLPFC (Ferraina, Paré, & Wurtz, 2001; Schall, 1997). As differences in *f*ERPs recorded in this current study began appearing as early as 50 ms following the onset of each fixation, results seemed to suggest an increased demand in translating the visual stimuli into appropriate motor responses when secondary cognitive task demand was high. This reduction in the processing of information following fixation onset was supported by current behavioural data indicating a significant increase in VTs.

In the prosaccade task the average activity of ERPs was significantly more positive going at central parietal and ocipito-parietal sites around the time of correct button presses in the low as compared to the high cognitive task demand condition. As the posterior parietal cortex (PPC) has been implicated in playing a major role in the "vision for action" system (Milner & Goodale, 1995, 2004) it could be argued that the transformation of visual information into motor commands is less efficient when secondary cognitive task demand is high. Furthermore results from this current study indicated that the reduction in activity in PPC coincided with significantly longer VTs and RTs. Taken together the data suggested that increases in cognitive load resulted in a reduction in the transformation of visual information into motor responses. This resulted in an increase in the time to verify a target as such, which in turn resulted in an increase in the overall time taken to correctly respond to a sudden onset target.

Effects of distraction on event related measures in the antisaccade task

In the antisaccade task results suggested that average activity of *f*ERPs at frontal as well as SEF sites was significantly more positive going in the low as compared to the high cognitive task demand condition. The prefrontal cortex has been implicated in a variety of different cognitive processes such as impulse control, planning and attention (for reviews see: Fuster, 1988; Levin, Eisenberg & Benton, 1991). Therefore the current study seemed to indicate that although the antisaccade task increased computational demands in the frontal cortex, the addition of a secondary cognitive task led to a reduction of activity in these areas following the onset of a fixation. It could be argued that the increase in cognitive task demand resulted in a decrease in the internally guided decision making and sequencing of eye movements, which was evidenced by an increase in first saccade error rates. Therefore results from this current study suggested that increases in cognitive task demand affected exogenous (prosaccades) and endogenous (antisaccades) in qualitatively different ways. Exogenously guided saccades seemed to require more activation in regions associated with the translation of visual input into motor responses, whereas endogenously guided eye movements were marked by a reduction in activity in areas associated with decision making, planning, inhibitory control and saccade sequencing.

For this same period around correct motor responses in the antisaccade task results indicated more positive going activity at frontal sites and the DLFPC when secondary cognitive task demand was high. Previous research provided evidence that the frontal lobes as well as the DLFPC play an integral role in executive functions such as inhibitory control, working memory and task switching (Corbetta et al., 2008).

As results indicated that preoccupation with solving a puzzle did not result in a decrease in overall response performance in the antisaccade task it could be reasoned that the increase in activity at frontal and DLPFC sites may be indicative of increases in computational and storage demands required to process both the antisaccade and the puzzle tasks simultaneously.

Effects of distraction on frequency measures in both pro- and antisaccade tasks

Alpha and theta frequency band power have been found to reflect changes in attentional demands whereas beta activity is thought to reflect appropriate emotional and cognitive processing (Ray & Cole, 1985). This current study demonstrated that over a one-minute period of prosaccades, overall theta was marginally reduced at a single electrode site in the high as compared to the low cognitive task demand condition. Not only was this finding in contrast to previous research, but the amount of inter-subject variability was too large to be able to make any claims as to the reliability of this result. However alpha band output was significantly lower at a large number of cortical sites in the high compared to the low cognitive load condition. This was the case for the full period of both the pro- and antisaccade task. These findings were in support of previous research that suggested that attentional and semantic memory demands may be seminal factors which lead to a selective suppression of alpha frequency (Klimesch et al., 1994; Klimesch et al., 1996; Klimesch et al., 1997) Alpha frequency is known to show large interindividual differences relating to age and memory performance (Klimesch et al., 1996) however the differences observed between high and low cognitive load conditions in this current study were more reliable than the differences observed in theta band energy. Furthermore, in the prosaccade task average beta energy was significantly lower in the high compared to the low cognitive task demand condition, however we found no main effect of cognitive load in the antisaccade task. Previous research has suggested that differences in beta output may reflect changes in both cognitive and emotional dimensions. Findings from these studies imply that beta energy may be a useful measure of appropriate cognitive and emotional processing (Ray & Cole, 1985). Results from this current study supported the notion that when the primary task was easy (prosaccade task) beta energy output may be a useful indicator of secondary cognitive processing. However when the primary task was difficult (antisaccade task) this measure showed no reliable dissociation between high and low cognitive task demand conditions. In human adults, alpha frequency is the dominant frequency in scalp EEG, whereas theta has been shown to be the dominant rhythm in the hippocampus of lower mammals. It should also be noted that the frequency range of the theta band (4-7 Hz) is much smaller than that of the alpha band (8-15 Hz) which makes it much more difficult to detect cortically without sophisticated methods (Klimesch, 1996). Taken together results from this study indicated that changes in tonic alpha output may be a more reliable indicator of secondary cognitive task demand than changes in theta band power. We did not observe any main effects of cognitive load or type of task on event related synchronisation of theta or event related desynchronisation of alpha rhythms following the target onset. This could indicate that phasic differences in frequency oscillations may be sensitive to the type of primary task and may only be observed in certain conditions. Another factor that may have influenced these results is the nature of the pro- and antisaccade task itself. This current experiment had more target onset events in one minute than previous transportation research reporting event-related de/synchronisation (Lin et al., 2011) This means to say that the repetitive and fast paced nature of the pro- and antisaccade tasks may have washed out these sensitive phasic differences in frequency band energy.

Target direction effects following target onset

Regardless of the type of task, average activity was significantly more positive going when the target appeared on the left as compared to the right hand side of the screen. We found no interaction between electrode site and the direction of the target, the type of task or cognitive load. This suggested that the increase of activity was not restricted to individual sites and is not modulated by cognitive load or the type of task. Previous experiments have reported left / right differences in the response times of prosaccades. Typically saccades to left side cued targets were slightly faster than to right side cued targets (Roberts et al., 1994). Furthermore, in an antisaccade task, it has been demonstrated that increases in concurrent arithmetic load produced slightly more incorrect reflexive prosaccades to leftward appearing targets compared to targets appearing on the right. It was reasoned that if arithmetic load produced a disproportionate amount of processing in the left hemisphere (Ashcraft, Yamashita & Aram, 1992; Earle, 1988) and if correct antisaccades to the right hemi field were programmed in the left hemisphere the additional load in the left side of the brain may have interfered with processes involved in inhibiting reflexive responses or generating antisaccades (Roberts et al., 1994). The secondary cognitive task in this current study was a puzzle-solving task that did not place a disproportionate amount of load on either hemisphere. Thus electrophysiological results seemed to suggest that laterality effects found in previous experiments may be a result of a general increase in cortical activity following leftward appearing targets. This may reflect a general preference or propensity for objects appearing in the left hemi field.

Comparison of current measures to those recorded in previous video based paradigms

Oculomotor measures that showed similar susceptibility to cognitive load between complex video based and the current low-level visual attention paradigms were saccade peak velocities, blink rates and the general spread of fixations. Furthermore blink durations seemed to be indicative of increases in the interaction of secondary cognitive load and processes relating to executive control but were not greatly affected by any single process in isolation. Savage et al. (2013) found no effect of cognitive load on blink durations, which was most likely due to the fact that no executive function manipulations were carried out. Results from current pro- and antisaccade tasks indicated that blink rates were most likely affected greatest when both processes relating to executive function and secondary cognitive task demand were high.

Behavioural data indicated that button press performance rates were not affected, however RTs and VTs were significantly longer in antisaccade task as well as in the high cognitive load condition. As predicted by models of executive control of attention (e.g., Norman & Shallice, 1986, Corbetta et al., 2008, Wickens, 2008), the effect of secondary cognitive load was attenuated when the primary task was difficult (antisaccade task). Finally, this current study demonstrated that alpha desynchronisation might be a more reliable indicator of secondary cognitive load than theta band synchronisation.

Conclusions

It was argued that examining the effects of cognitive load on individual component processes of hazard perception might aid in the understanding of the observed decrements in hazard perception performance. The first experimental chapter of the current thesis was therefore aimed at determining the susceptibility of processes of alerting, orienting and inhibitory control to variations in secondary cognitive task demand. Increased cognitive load resulted longer first saccade latencies, larger first saccade error rates and therefore longer overall time to hit the target. This current study suggested that cognitive distraction resulted in an interference with processes of inhibitory control as well as both reflexive and volitional control and execution of eye movements. This may suggest that detriments observed in a more complex hazard perception task may be due to cognitive load interfering with these sub component processes.

Another component related to successful hazard perception is the ability to search through a visual scene and identify one object as a hazard as opposed to any other (Horswill & McKenna, 2004). Processes of visual search are important in any visually driven task and this is especially true for hazard perception tasks in which participant are required to search and identify hazards in a dynamic visual scene. Therefore the following experimental chapter was aimed at determining the effects of cognitive load on processes of visual search in a more visually low-level search paradigm.

Chapter III

The effect of secondary cognitive task demand on processes of visual search.

Introduction

The previous experiment of this thesis was aimed at determining whether decrements in hazard perception performance could, to some extent, be explained by secondary cognitive task demand interfering with processes of alerting, orienting and inhibitory control. Results indicated that when secondary cognitive load was high, alerting, reflexive orienting of visual attention, as well as processes relating to inhibitory control were significantly impaired. A vital component of hazard perception is the ability to search through a dynamic visual scene and identify hazards by a subtle set of characteristics (Horswill & McKenna, 2004). Therefore the aim of this current experiment was to consider whether previously observed decrements in hazard perception might be related to impairments in processes of visual search.

Contrary to low-level visual search tasks, targets in hazard perception paradigms are more often than not defined by context rather than a specific set of visual features. This means to say that subjects are not told what the hazard looks like prior to the onset of the primary task but are required to utilize a set of rules (the “rules of the road”) to determine what is and what is not a target. It is therefore acknowledged that visual search during hazard perception may rely much more heavily on higher-level executive functions compared to low-level visual search tasks. Nonetheless it has been argued that low-level visual search tasks, or more specifically the distribution of fixations within low-level visual search tasks, may indicate a systematic component to search behaviour (Gilchrist & Harvey, 2006). In standard visual search paradigms participants are presented with a series of arrays and are instructed to decide whether a predefined target is present or not. Typically the target is present on 50% of trials. In hazard perception tasks there are periods during the clip in which a potential hazard is present as well as periods during which no hazards are on screen. Successful hazard perception performance therefore relies on participants not only correctly identifying hazards but also not reacting to non-hazardous stimuli. Examining the susceptibility of the components of visual search to secondary cognitive load may to some extent help account for the detriments observed in the more complex hazard perception task.

Previous research by Gilchrist and Harvey (2006) attempted to detect the presence of a strategic component in visual search behaviour by following Williams' (1966) claim that there is often a directionality to successive fixations. As it was argued that the analysis of saccade directions has the potential to reveal strategic components within visual search, Gilchrist and Harvey (2006) analysed the frequency of saccades in different directions across arrays of varying structural consistency. Results from their study not only indicated a strong systematic component within visual search but that the extent of systematic scanning was modulated by the structure of the display. Regular grid structures led to participants generating more horizontal than vertical saccades. While disrupting the display regularity led to a change in the distribution of saccade directions, it did not result in the elimination of this systematic component within search behaviour. Previous research has demonstrated that additional secondary cognitive load increases response times in visual search tasks (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). One issue that remains to be determined is whether and to what extent this systematic component is affected by secondary cognitive task demand and to what extent display regularity and cognitive load might interact to influence search behaviour.

As hazard perception relies on the ability to search through dynamic visual scenes in order identify hazards, the aim of this current experiment was to determine the extent to which secondary cognitive task demand interferes with processes of visual search. More specifically we were interested in determining the effects of ruminating on a previously heard puzzle on strategic components within a low-level visual search paradigm. To this effect we replicated Gilchrist and Harvey's (2006) structured and unstructured visual search paradigm in which participants were required to search for a target and make a present/absent decision with the addition of Savage, Potter & Tatler's (2013) secondary puzzle task. Previous research has focussed on identifying factors that determine where we look as well as how we move our eyes across visual scenes (Tatler & Vincent, 2009). It has been argued that viewing behaviour is influenced by biomechanical factors (Smit, Van Gisbergen & Cools, 1987; Viviani, Berthoz & Tracey, 1977), the distribution of objects in the scene (Land et al., 1999; Lewis, Garcia & Zhaoping, 2003), the features of individual objects or locations (Itti & Koch, 2000; Parkhurst et al., 2002) as well as individual strategies (Gilchrist & Harvey, 2006) which can vary across different tasks (Rayner et al., 2007; Tatler et al., 2006).

Eye movements are intimately linked to attention (Henderson, 2003; Hutton, 2008) and as such have become a valuable tool with which to investigate the perceptual processes involved between the onset of any given stimulus and the following motor response (Findlay, 1997; Zelinsky & Sheinberg, 1997). Most models of visual search, especially those focussing on saccade generation emphasise the role of bottom up saliency driven mechanisms on how eye movements are guided through a visual scene (e.g., Itti & Koch, 2000). It is thought that the salience of each object is determined by a competitive process between a set of low-level features (i.e. orientation-, colour- and luminance-contrast); and that these are accumulated to form an overall saliency map of the scene. Fixations are then allocated to locations with the highest saliency first. This is argued to be the process by which both saccades (Findlay & Walker, 1999, Itti & Koch, 2000) and attention (Wolfe, 1994) are allocated to items within in a visual scene. However more recently research has shown that purely saliency-based models are not accurate in terms of predicting where participants would fixate next (Tatler, 2007; Tatler, Baddeley & Vincent, 2006, Tatler, Baddeley & Gilchrist, 2005) Previous work seems to suggest that saccades have a directional bias and that this bias reflects a systematic rather than a random process (Williams, 1966; Norton & Stark, 1971; Yarbus, 1967). It could be argued that systematic scanning is a result of higher-level processes or strategies; therefore one would expect a reduction of this systematic component when secondary cognitive task demand was high. Conversely if systematic scanning requires no effortful top-down control but is a process intended to free up resources and guide visual search when secondary cognitive task demand is high, one might expect an increase in this systematic component. Finally it could be argued that secondary cognitive task demand does not interfere at all in the process of determining the position of each successive fixation but interferes with the overall spread at which we perform our visual search. This would be reflected in a significant reduction in overall spread of fixations along the vertical or horizontal axis as previously found in hazard perception (Savage et al., 2013) and simulated driving tasks (e.g., Recarte & Nunes, 2003)

In addition to examining the susceptibility of traditional visual search task measures to increases in secondary cognitive load, we were also interested in determining the extent to which oculomotor signatures of cognitive distraction found in Savage, Potter and Tatler's (2013) hazard perception task were present in this, more low-level, visual search task. If changes in oculomotor metrics resulting from increases in secondary cognitive load are similar between video based hazard perception and low-level visual search tasks, then these metrics may be indicative of increased cognitive load in general, regardless of the primary task. Alternatively it could be reasoned that detriments observed in hazard perception tasks are due to cognitive load interfering with processes of visual search. The current study included measures of blink durations, blink frequencies, spread of fixations along the x-axis as well as overall saccade peak velocities, first saccade peak velocities and changes in saccade peak velocities over time, as these measures have previously been shown to be affected by cognitive task demand.

Previous research has demonstrated that peak velocities decrease as a function of time on task (Galley, 1993; DiStasi, 2012), which has been interpreted within a mental fatigue account: higher mental fatigue leading to slower peak velocities. Furthermore, as peak velocities have been shown to be sensitive to variations in mental activation (App & Debus, 1998), alertness (Thomas & Russo, 2007), mental workload (Savage et al., 2013; Di Stasi et al., 2010) as well as drug-induced sedation, sleep deprivation and fatigue (Grace et al., 2010; Zils et al., 2005, Schmidt et al., 1979), this current study was aimed at determining not only the effect of time on task but also the interaction between time and cognitive load on saccade peak velocities.

The number of fixations and refixations has been thought to reflect the level of processing which has gone into each item of the display: more refixations reflecting more frequent incomplete processing or less memory for previously fixated items (Gilchrist and Harvey, 2000, Peterson et al, 2001). We argue that if high-level executive functions such as working memory are required to keep in mind previously processed distractor locations then one should expect an increase in refixations within the high compared to the low cognitive load condition. Research by Solman, Cheyne and Smilek (2011) has shown that a concurrent secondary memory task affected not only response times, but also initial encoding and response selection phases.

Therefore we were interested in determining the effect of secondary cognitive task demand on measures of VT (Verification Time – the time between the final fixation upon the target and the following manual response) and the number of fixations. In Experiment I first saccade latencies were longer when cognitive load was high. In the current study we were interested in determining the effect of secondary cognitive task demand on first saccade latencies when there was no prior alerting signal. As fixation durations have been associated with visual processing demands (Droll, Hayhoe, Triesch & Sulllivan, 2005; Hayhoe et al., 2003) we were interested in determining whether secondary cognitive load interfered with visual processing. Finally, visual search performance is significantly slowed by the addition of a secondary cognitive task (Oh & Kim, 2004; Woodman & Luck, 2004) we expected a significant increase in reaction times. However by tracking participants' eye movements we were able to identify the cause of the observed increases in RTs.

Methods

Design

In this 2 x 2 within subjects design the independent variables were cognitive load, which was either high or low (puzzle = high; easy question = low), and search array structure which was either structured or unstructured. Dependent variables can be grouped into two major categories: 1) behavioural and 2) oculomotor. Behavioural measures consisted of RTs, VTs and Response Performance (correctly identifying the presence or absence or the target). Oculomotor metrics consisted of time to hit, number of fixations, number of refixations, fixation durations, spread of fixations along the horizontal and vertical axes, saccade directions, saccade amplitudes, saccade durations, first saccade peak velocities, average saccade peak velocities, blink frequencies and blink rates.

Participants

15 participants (7 male and 8 female, age range 17- 33) were recruited in and around the University of Dundee by means of the Universities Research Participation System “SONA”. All testing was carried out in the Research Wing of the School of Psychology at the University of Dundee. Participation lasted no longer that 45 minutes and participants were compensated with course credit or chocolate for their participation.

Materials

Participants sat at a table with their heads supported by a chinrest 85 cm away from a 19*”* CRT-Monitor on which the visual stimuli were displayed with a resolution of 1024x768 pixels. Experiment Builder software by SR-Research was used to program the presentation of the audio and visual stimuli. We replicated and modified Gilchrist & Harvey’s (2006) visual search paradigm to include a secondary cognitive dual task. In all conditions the target in the primary visual search task was a white upward facing triangle and distractor items consisted of white downward and rightward facing triangles. The display size always consisted of 25 items (1x1° visual angle), with 12 of each type of distractor. In the case when the target was not present it was replaced by one of the distractor types (randomly selected). In the structured condition, 25 items were placed randomly onto the junctions of an invisible 5x5 grid resulting in no free placeholders and thus a spatially structured array (e.g., Figure 1, left). In the unstructured condition the same 25 items were placed randomly onto the junctions of a 7x7 grid, leaving 24 randomly selected blank locations in each trial resulting in a spatially unstructured search array (e.g., Figure 1, right). Across both conditions the overall display size was kept constant (12x12° visual angle.) resulting in structured and unstructured search arrays, which subtend the same visual space. We made use of the same lateral thinking puzzles and easy questions to manipulate secondary cognitive task demand as in the previous experiment of this current thesis. These questions and riddles were presented via a set of Logitech loudspeakers at a comfortable and constant volume, which was regulated individually for each participant.

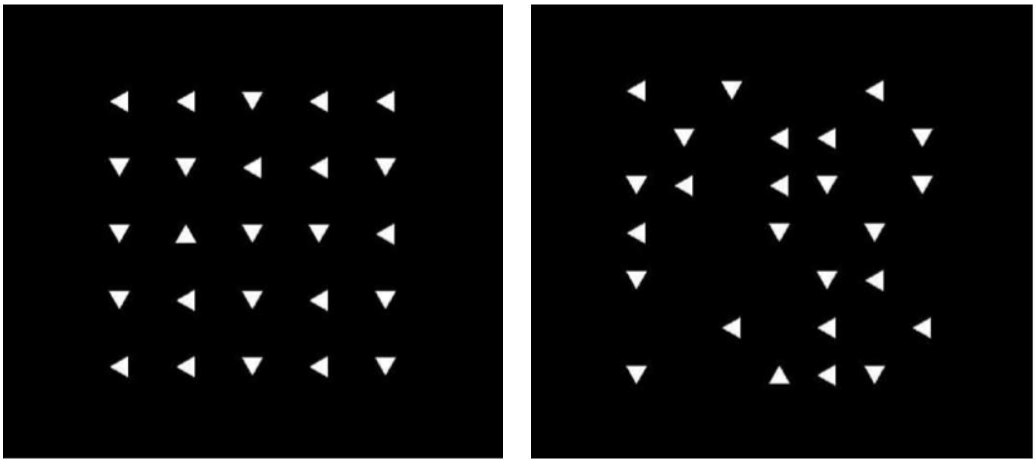


Figure 1, *Example displays of both structured (left panel) and unstructured (right panel) search arrays (reproduced from Gilchrist & Harvey, 2006).*

<u>Procedure</u>

A white fixation disc was presented at the beginning of each block of visual search trials in order to check for any spatial offset in the calculated eye position. Participants were either presented with a puzzle ('high-load' i.e. "*What can pass through water without getting wet?*") or an easy question ('low-load' i.e. "*What city are you in?*") directly prior to the start of each (1-minute) block of 16 search trials. We utilised the same questions and riddles as in Experiment 1. Trials of high/low secondary cognitive task demand were presented randomly but interleaved within each condition of 'structure'. The structured and unstructured search arrays were presented in blocks, which were counterbalanced for presentation order across all participants. In the primary visual search task, participants were required to make a target present/absent response using the one of two button boxes provided. For a target present decision subjects were required to press the button box in their right hand and for target absent choices the button box in their left hand.

At the end of each 1-minute block there was a brief intermission in which participants were asked to indicate whether they knew the question and whether they had managed to solve the question (and to state their answer). This information was relevant only for high load questions. All together participants completed 320 structured (160 high load & 160 low load) and 320 unstructured (160 high load & 160 low load) search trials.

Eye Movement recording

Eye movements were recorded using an SR-Research EyeLink1000 eye-tracker, sampling at 1000 Hz. Each participant completed three brief eye dominance tests prior to the start of testing so that the experimenter was able to track the subject's dominant eye. A 9-point calibration procedure was used to calibrate the tracker and repeated to validate tracker accuracy. If the validation procedure showed an average error in excess of 0.5° or a maximum error in excess of 1°, the calibration procedure was repeated. Single-point calibration checks were performed at the beginning of each block of trials. Saccades were identified using the standard SR-Research algorithm, which detects saccades when eye position deviates by more than 0.1°, with a minimum velocity of 30 deg s^{-1} and a minimum acceleration of 8000 deg s^{-1}, maintained for at least 4 ms. Data were exported via custom-made Matlab routines for subsequent analysis of saccade, fixation and blink events.

Statistical Analysis

To determine the impact of secondary cognitive task demand and structure on behavioural and oculomotor measures, data were analysed by means of Linear Mixed Models (LMMs) using the *lme4* package (version 1.1-7; Bates et al., 2014) in the *"*R*"* statistical programming environment (R Development Core Team, 2007). LMMs are particularly well suited to datasets such as those collected in this study for several reasons: 1) they are able to deal with uneven distributions of data between conditions in the design; 2) they can combine continuous and categorical factors within the same model; and 3) they can measure variance across subjects and items simultaneously (Kliegl et al 2012). In constructing models, structure (structured or unstructured) and cognitive load (high or low) were entered as fixed effects whereas subjects, trial number and block number were entered as random effects. For the random effects structure we attempted to include random slopes and intercepts for all fixed effects and their interactions in order to produce a maximal random effects structure (Barr et al., 2013). However, maximal structure models often fail to converge. When these models did not converge, we first removed the computation of correlation parameters within the random effects structures. If further simplification was required for convergence, we began by simplifying the block term first. To this effect we first removed the interaction between structure and load. Next we removed the random slope for load before removing the random slope for structure. Throughout this simplification process, the full random effect structure for both trial number and subject was retained (without correlation parameters). However, if further simplification was required the procedure described above was repeated stepwise first on the trial then on the subject term. In the sections that follow the results are reported for the most complex random effects structure for which the LMM converged. *P*-values for structure, cognitive load and the interaction between these two variables were calculated by means of model comparisons. To this effect LMMs were created without the fixed factor (or interaction) for which the *p*-value was to be determined. This resulted in three additional models, one without structure as a fixed effect, one without cognitive load as a fixed effect and one without the interaction between these two factors. These baseline models were compared individually to the original LMM by means of three analyses of variance (ANOVAs).

Results

<u>*Behavioural consequences of preoccupation*</u>

Average RTs, FRs and VTs for both structured and unstructured search arrays between high and low cognitive load conditions along with their appropriate standard errors can be seen in Table 1.

Table 1, *RTs, VTs and Response Performance (Perf.) for both structured and unstructured conditions, between high (HL) and low cognitive load (LL) trials for both target present and target absent trials along with appropriate standard errors (SE).*

	Target Present				**Target Absent**			
	Structured		Unstructured		Structured		Unstructured	
	HL	**LL**	**HL**	**LL**	**HL**	**LL**	**HL**	**LL**
RTs [2,5]	2644.12	1896.14	3016.66	2201.3	4223.72	3260.79	4539.88	3591.17
	(57.16)	*(41.89)*	*(67.05)*	*(47.22)*	*(66.26)*	*(45.42)*	*(64.05)*	*(44.12)*
VTs [1,2]	594.05	259.19	756.93	382.86	*NA*	*NA*	*NA*	*NA*
	(35.97)	*(18.56)*	*(42.83)*	*(25.71)*				
Perf. [1,5]	.82	.85	.77	.80	.98	.99	.99	.99
	(.012)	*(.011)*	*(.013)*	*(.013)*	*(.004)*	*(.002)*	*(.003)*	*(.001)*

1 Significant main effect of 'Structure' in Target Present Trials
2 Significant main effect of 'Load' in Target Present Trials
3 Significant Interaction between 'Load' and 'Structure' in Target Present Trials
4 Significant main effect of 'Structure' in Target Absent Trials
5 Significant main effect of 'Load' in Target Absent Trials
6 Significant Interaction between 'Load' and 'Structure' in Target Present Trials

RTs

When the target was present, RTs were significantly slower in the high compared to low cognitive load condition (b= -.13; SE= .041, t= - 3.15; p= .004) but were not affected by the structure of the array (b= .07; SE= .04; t = 1.83; p= .073) however we found no interaction between structure and load (b= .004; SE= .04; t = .1; p= .092).

When the target was absent RTs were significantly slower in the high cognitive load condition (*b*= -.094; *SE*= .024; *t*= -3.92; *p*< .001) but were not affected by the structure of the array (*b*= .05; *SE*= .036; *t*= 1.5; *p*= .14). Finally we found no interaction between load and structure on participants RTs (*b*= .003; *SE*= .03; *t* = .13; *p*= .89).

VTs

Verification times were analysed only on trials when the target was present. VTs were significantly slower in the high compared to the low cognitive task demand condition (*b*= -341.93; *SE*= 109.34; *t*= -3.13; *p*= .004) and significantly slower in unstructured compared to the structured condition (*b*= 145.94; *SE*= 48.15; *t*= 3.03; *p*< .001). However we found no interaction between cognitive load and structure (*b*= -34.02; *SE*= 142.71; *t*= -.24; *p*= .81).

Response Performance

When the target was present overall motor response performance was not affected by cognitive load (*b*= .21; *SE*= .2; *z*= 1.07; *p*= .29) but was significantly lower in the unstructured compared to the structured condition (*b*= -.33; *SE*= .1; *z*= -3.28, *p* = .006). When the target was absent response performance was lower in the high compared to the low cognitive load condition (*b*= 1.63; *SE*= .51; *z*= 3.22; *p* < .001) but was not affected by the structure of the array (*b*= .59; *SE*= .56; *z*= 1.07; *p*= .29). We found no interaction between cognitive load and structure (*b*= -.27; *SE*= 1.01; *z*= -.27; *p*= .79).

Effects of preoccupation on oculomotor measures

Averages for oculomotor measures for both structured and unstructured as well as between high and low cognitive load conditions for both target present and absent trials along with their appropriate standard errors can be seen in Table 2.

Table 2, *Summary of oculomotor measures for unstructured and structured conditions between high (HL) and low load (LL) trials for both target present (TP) and target absent (TA) trials along with appropriate standard errors in paretheses.*

	Target Present				**Target Absent**			
	Structured		*Unstructured*		*Structured*		*Unstructured*	
	HL	**LL**	**HL**	**LL**	**HL**	**LL**	**HL**	**LL**
N Fix. [1,2,5]	9.39	7.66	11.12	8.98	15.59	13.37	17.44	14.88
	(.18)	*(.15)*	*(.21)*	*(.18)*	*(.2)*	*(.16)*	*(.22)*	*(.16)*
N Refix. [1,2,4,5]	1.03	0.66	1.89	1.25	1.64	1.03	3.06	2.01
	(.04)	*(.03)*	*(.07)*	*(.05)*	*(.06)*	*(.04)*	*(.1)*	*(.07)*
Fix. Durs. [2,5]	232.39	208.56	232.26	208.96	227.11	207.87	223.41	209.09
	(1.34)	*(1.09)*	*(1.17)*	*(1.02)*	*(.85)*	*(.74)*	*(.77)*	*(.71)*
First SPV	282.78	278.86	276.32	259.88	281.4	294.37	270.52	264.41
	(5.98)	*(4.52)*	*(5.89)*	*(4.27)*	*(6.54)*	*(5.65)*	*(6.1)*	*(5.39)*
Average SPV [2,5]	295.53	303.36	285.2	293.95	317.88	335.06	309.07	317.05
	(1.59)	*(1.61)*	*(1.49)*	*(1.63)*	*(1.13)*	*(1.23)*	*(1.2)*	*(1.28)*
First Sac. Lat. [2,5]	259.34	246.79	248.1	235.13	272.2	252.42	254.62	229.69
	(3.51)	*(3.2)*	*(3.25)*	*(2.78)*	*(4.24)*	*(3.49)*	*(3.36)*	*(2.58)*
Saccade Amp.	3.98	395	3.84	3.89	4.4	4.53	4.29	4.39
	(.03)	*(.03)*	*(.03)*	*(.03)*	*(.02)*	*(.02)*	*(.02)*	*(.02)*
Saccade Durs [4]	37.41	38.22	36.21	36.47	39.84	40.42	38.33	38.49
	(.19)	*(.22)*	*(.17)*	*(.18)*	*(.16)*	*(.14)*	*(.13)*	*(.14)*
Time To Hit [2]	929.62	744.32	129.6	852.91	***NA***	***NA***	***NA***	***NA***
	(44.17)	(34.57)	(53.35)	(40.19)				
X Spread [5]	96.11	97.14	97.94	98.42	96.12	100.75	98.25	100.8
	(61.49)	*(61.89)*	*(62.11)*	*(61.89)*	*(62.03)*	*(62.47)*	*(62.98)*	*(62.54)*
Y Spread	107	104.53	105.11	103.5	106.3	108.44	105.97	108.26
	(66.28)	*(64.34)*	*(63.26)*	*(62.3)*	*(65.11)*	*(64.74)*	*(63.66)*	*(62.55)*

1 Significant main effect of 'Structure' in Target Present Trials
2 Significant main effect of 'Load' in Target Present Trials
3 Significant Interaction between 'Load' and 'Structure' in Target Present Trials
4 Significant main effect of 'Structure' in Target Absent Trials
5 Significant main effect of 'Load' in Target Absent Trials
6 Significant Interaction between 'Load' and 'Structure' in Target Present Trials

In table 2 abbreviations of measures stand for the following: N-Fix – Number of Fixations, N Refix – Number of refixations, Fix Durs – Fixation durations, First SPV – First saccade peak velocities, Average SPVs – Average saccade peak velocities, First Sac Lat – First Saccade latencies, Saccade Amp - Saccade Amplitudes, Saccade Durs – Saccade Durations.

Total Number of Fixations

When the target was present, participants made significantly more fixations in the high compared to the low cognitive load condition (*b*= -1.86; *SE*= .65; *t*= -2.86; *p*= .008) as well as in the unstructured compared to the structured condition (*b*= 1.56; *SE*= .68; *t*= 2.29; *p*= .03).

When the target was absent, the number of fixations was higher in the high compared to the low cognitive load condition (*b*= -2.28; *SE*= .7; *t*= -3.26; *p*= .003) but was not affected by the structure of the array (*b*= 1.77; *SE*= 1.12; *t*= 1.58; *p*= .12). Finally we found no interaction between load and the structure of the array (*b*= -.44; *SE*= .76; *t*= .57; *p*= .56).

Number of Refixations

When the target was present refixations were significantly more frequent in the high compared to the low cognitive load condition (*b*= -.5; *SE*= .15; *t*= -3.44; *p*= .002) as well as in the unstructured compared to the structured search array (*b*= .73; *SE*= .14; *t*= 5.08; *p*< .001). However we found no interaction between structure and load (*b*= -.27; *SE*= .21; *t*= -1.3; *p*= .56).

Similarly, when the target was absent refixations were more frequent in the high compared to the low cognitive load condition (*b*= -.8; *SE*= .26; *t*= -3.08; *p*= .008) as well as in unstructured compared to the structured trials (*b*= 1.22; *SE*= .31; *t*= 3.88;

$p < .001$). We found no interaction between structure and load ($b = -.46$; $SE = .27$; $t = -1.68$; $p = .09$) on the number of refixations.

Fixation Durations

When the target was present fixation durations were significantly longer in the high compared to the low cognitive load condition ($b = -.04$; $SE = .01$, $t = -3.42$; $p = .002$) but were not affected by structure ($b = .003$, $SE = .001$, $t = .43$; $p = .66$).

We found no interaction between structure and cognitive load ($b = -.0003$; $SE = .01$, $t = -.04$; $p = .97$). When the target was absent fixation durations were longer in the high compared to the low cognitive load condition ($b = -.03$; $SE = .007$, $t = -4.26$; $p < .001$) but were unaffected by structure ($b = -.0004$; $SE = .008$; $t = -.05$; $p = .96$). Furthermore we found no interaction between cognitive load and structure ($b = -.008$; $SE = .008$; $t = .95$; $p = .34$).

First saccade latency

When the target was present first saccade latencies were significantly longer in the high compared to the low cognitive load condition ($b = -.019$; $SE = .007$; $t = -2.71$; $p = .012$) but were not affected by structure ($b = -.018$; $SE = .012$; $t = -1.42$; $p = .15$). Furthermore we found no interaction between load and structure ($b = -.003$; $SE = .01$; $t = -.3$; $p = .76$).

When the target was absent first saccade latencies were significantly longer in the high compared to the low cognitive load condition ($b = -.034$; $SE = .008$; $t = -3.94$; $p < .001$). However we found no effect of structure ($b = -.026$; $SE = .015$; $t = -1.76$; $p = .08$) as well as no interaction between the two independent variables ($b = -.019$; $SE = .015$; $t = -1.24$; $p = .21$).

First Saccade peak velocity

When the target was present first saccade peak velocities were not affected by cognitive load (*b*= 9.21; *SE*= 10.09; *t*= -.91; *p*= .35) or by structure (*b*= 12.93; *SE*= 13.64; t = -.94) and we found no interaction between the two independent variables (*b*= -11.53; *SE*= 12.32; *t*= -.94; *p*= .34).

Similarly, when the target was absent first saccade peak velocities were not affected by cognitive load (*b*= 1.89; *SE*= 11.33; *t*= .17; *p*= .86) or by structure (*b*= -18.87; *SE*= 11.54; *t*= -1.64; *p*= .1). Furthermore we found no significant interaction between cognitive load and structure (*b*= -19.54; *SE*= 19.66; *t*= -.99; *p*= .31).

Overall Saccade Peak velocity

When the target was present, overall saccade peak velocities were slower in the high compared to the low cognitive load condition (*b* = 11.56; *SE* = 4.88; *t* = 2.37; p= .023) but were not affected by structure (*b* = -5.03; *SE* = 13.1; *t* = -.38; p= .69). We also did not find an interaction between load and structure (*b* = -2.29; *SE* = 4.9; *t* = -.47; *p*= .63).

When the target was absent, overall peak velocities were slower in the high compared to the low cognitive load condition (*b* = 14.29; *SE* = 6.24; *t* = 2.29; *p*= .03) but were not affected by structure (*b* = -9.66; *SE* = 13.56; *t* = -.71; *p*= .47). Furthermore we found no interaction between cognitive load and structure (*b* = -11.73; *SE* = 6.42; *t* = -1.83; *p*= .73).

Saccade Durations

When the target was present saccade durations were not affected by cognitive load (*b* = .35; *SE* = .35; *t* = 1.04; *p*= .29) or by structure (*b* = -1.19; *SE* = .76; *t* = -1.57; *p*=

.12) and we found no interaction between cognitive load and structure (*b* = -.63; *SE* = .56; *t* = -1.13; *p*= .25).

However when the target was absent, saccade durations were longer in structured compared to unstructured trials (*b* = -1.52; *SE* = .72; *t* = --2.13; *p*= .04) but were not affected by cognitive load (*b* = .32; *SE* = .42; *t* = .75; *p*= .47). Furthermore we found no interaction between cognitive load and structure (*b* = -.63; *SE* = .54; *t* = -1.15; *p*= .24).

Saccade Amplitudes

When the target was present saccade amplitudes were not affected by either cognitive load (*b*= .054; *SE*= .049; *t*= 1.11; *p*= .62) or by structure (*b*= -.06; *SE*= .12; *t*= -.49; *p*= .26). Furthermore we found no interaction between load and structure (*b*= .03*; SE*= .09; *t*= .35; *p*= .71).

Similarly, when the target was absent, saccade amplitudes were not affected by cognitive load (*b*= .13; *SE*= .071; *t* = 1.77; *p*= .082) or by structure (*b* = -.15; *SE*= .12; *t*= -1.23; *p*= .21). Furthermore we found no significant interaction between cognitive load and structure (*b*= -.1*; SE*= .08; *t*= -*1*.34; *p*= .18).

Time to Hit

Time to hit was analysed only for trials in which the target was present. Results showed significantly longer time to hit in the high compared to the low cognitive load condition (*b*= -231.34; *SE*= 72.65; *t*= -3.18; *p*< .001) but no effect of structure (*b*= 166.23; *SE*= 109.79; *t*= 1.51; *p*= .13) and no interaction between the two independent variables (*b*= -77.11; *SE*= 111.03; *t*= -.7; *p*= .81).

Average spread of fixations along the X and Y-axes

Average spread was estimated by calculating the absolute distance for x & y fixation coordinates from the centre of the display. Results indicated that when the target was present, the overall spread of fixations along the x-axis was not affected by load (*b*= 1.54; *SE*= 1.49; *t* = 1.03; *p*= .3) or structure (*b*= 2.72; *SE*= 3.06; *t* = .89; *p*= .36). Furthermore there was no interaction between load and structure on the spread of fixations along the x-axis (*b*= -2.03; *SE*= 2.81; *t* = -.72; *p*= .46).

Similarly when the target was present there was no effect of load (*b*= -2.23; *SE*= 1.57; *t*= 1.42; *p*= .16) or structure (*b*= -1.07; *SE*= 3; *t*= .36; *p*= .72) and no interaction between these two variables (*b*= 1.1; *SE*= 2.78; *t*= .39; *p*= .69) on the spread of fixations along the y-axis.

When the target was absent the spread of fixations along the x-axis was marginally significantly reduced in the high compared to the low cognitive load condition (*b*= 3.19; *SE*= 1.61; *t* = 1.98; *p*= .054) but was not affected by structure (*b*= 1.87; *SE*= 2.79; *t* = .67; *p*= .49). Furthermore we found no interaction between load and structure (*b*= -2.24; *SE*= 2.49; *t* = .9; *p*= .29).

The spread of fixations along the y-axis when the target was absent was not affected by cognitive load (*b*= 2.49; *SE*= 1.99; *t* = 1.25; *p*= .21) or the structure of the array (*b*= .39; *SE*= 2.51; *t* = .15; *p*= .84) and we found no interaction between these two variables (*b*= .73; *SE*= 2.65; *t*= .28; *p*= .78).

Blink Rates and Durations

Blink rates and durations were analysed irrespective of target presence or absence. Blink durations were not affected by structure (*b*= .04; *SE*= .04; t= .95; p= .34) or load (*b*= -.04; *SE*= .03; *t*= -1.31; *p*= .19) and we found no interaction between load and structure (*b*= -.03; *SE*= .04; *t*= -.76; *p*= .44). Blink rates were significantly higher in the high compared to the low cognitive load condition (*b* = -4.49; *SE* = .91; *t* = -4.91; *p*< .001) but we found no effect of structure (*b*= -.63; *SE*= 1.34; *t*= -.47; *p*= .71) and no interaction between load and structure (*b*= 1.98; *SE*= 1.1; *t*= 1.8; *p*= .082). Average blink rates and durations for structured and unstructured arrays between high and low load conditions can be seen in Figures 2 and 3 respectively.

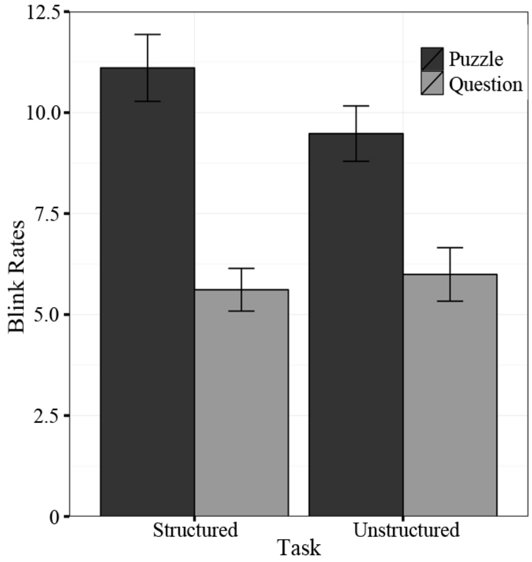


Figure 2, *Bar graph showing average blink rates for both structured and unstructured trials between high and low load conditions including error bars indicating 2 Standard Errors*

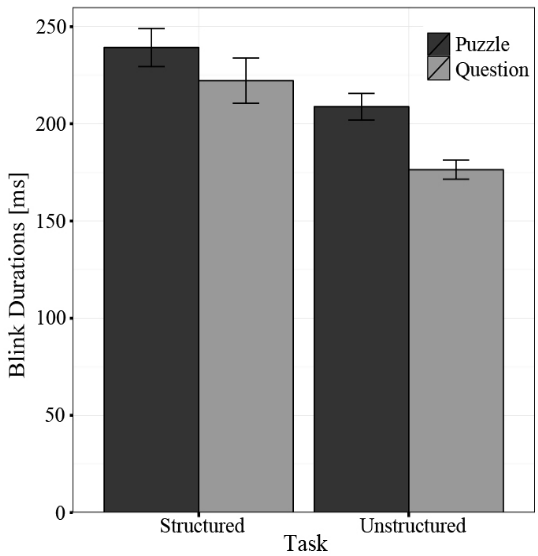


Figure 3, *Bar graph showing average blink durations for both structured and unstructured trials between high and low load conditions including error bars indicating 2 Standard Errors*

Saccade directions

Saccades were coded for direction in degrees with zero signifying saccades in a rightward direction. For each participant in each condition the frequency of all saccades within 20-degree bins were calculated. Prior to analysing the data, all saccades falling outwith the display area were excluded. LMMs are problematic for factors with multiple levels, as the direction bin factor had 18 levels (one bin for every 20 degrees) we analysed the interaction between load, structure and saccade direction distributions by means of an analysis of variance (ANOVA). A within-subjects ANOVA with structure, cognitive task demand and direction bins as within subjects factors, was carried out on the data in order to determine whether the frequencies of fixations within any particular direction bin were different between both structured and unstructured as well as high and low cognitive load conditions.

Therefore, we were primarily interested in the interaction between direction bins and structure as well as direction bins and cognitive load. We found a main effect of load ($F(1, 14) = 11.97$; $p = .004$), which indicated that more saccades were made in the high compared to the low load condition. A significant main effect of direction bin on saccade counts ($F(1, 14) = 14.24$; $p < .001$) suggested that saccades were being made in some directions more than others. More interestingly however were the significant interactions between the structure of the array and saccade direction ($F(17, 238) = 2.58$; $p < .001$) as well as cognitive load and saccade direction ($F(17, 238) = 2.38$; $p = .002$). These interactions indicated that cognitive load as well as structure resulted in changes in the directionality of saccades. The interaction between load and saccade directions can be seen in Figure 4, whereas the interaction between structure and saccade directions can be seen in Figure 5.

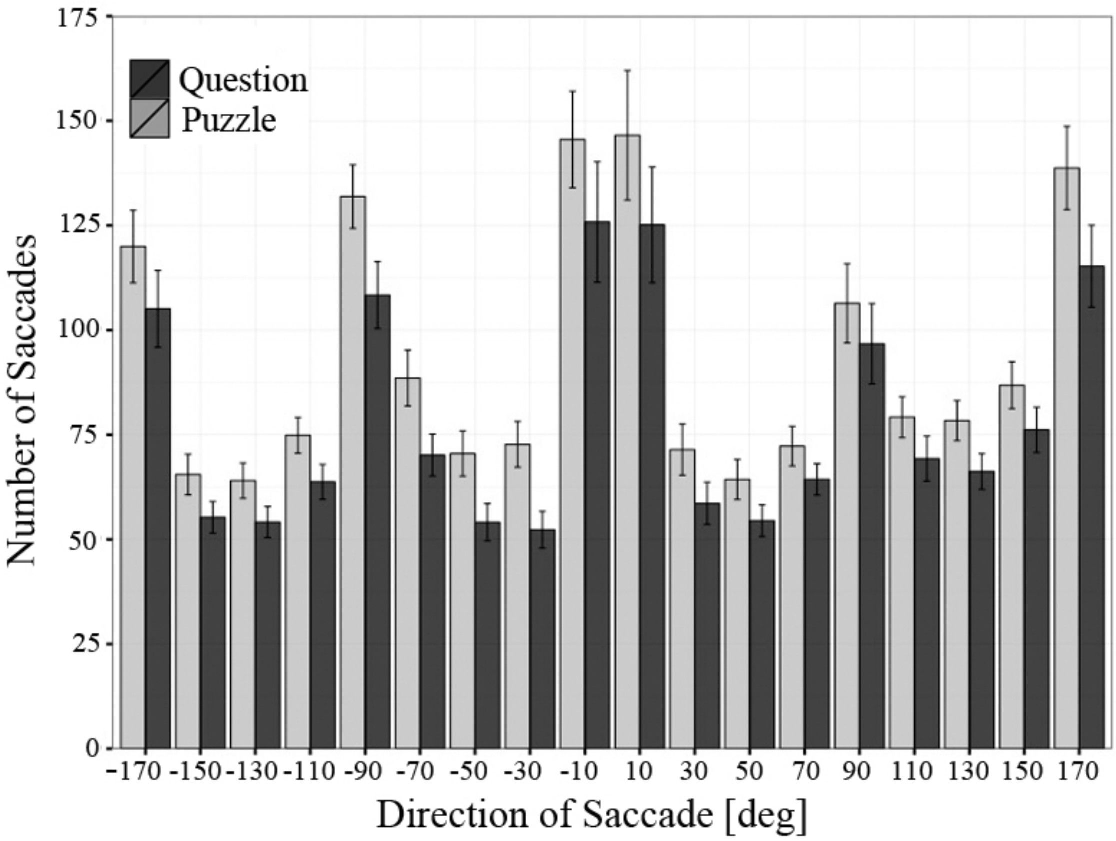


Figure 4, *Bar graph plotting the frequency of saccades in each given direction bin between high and low load condition including error bars indicating 2 standard errors.*

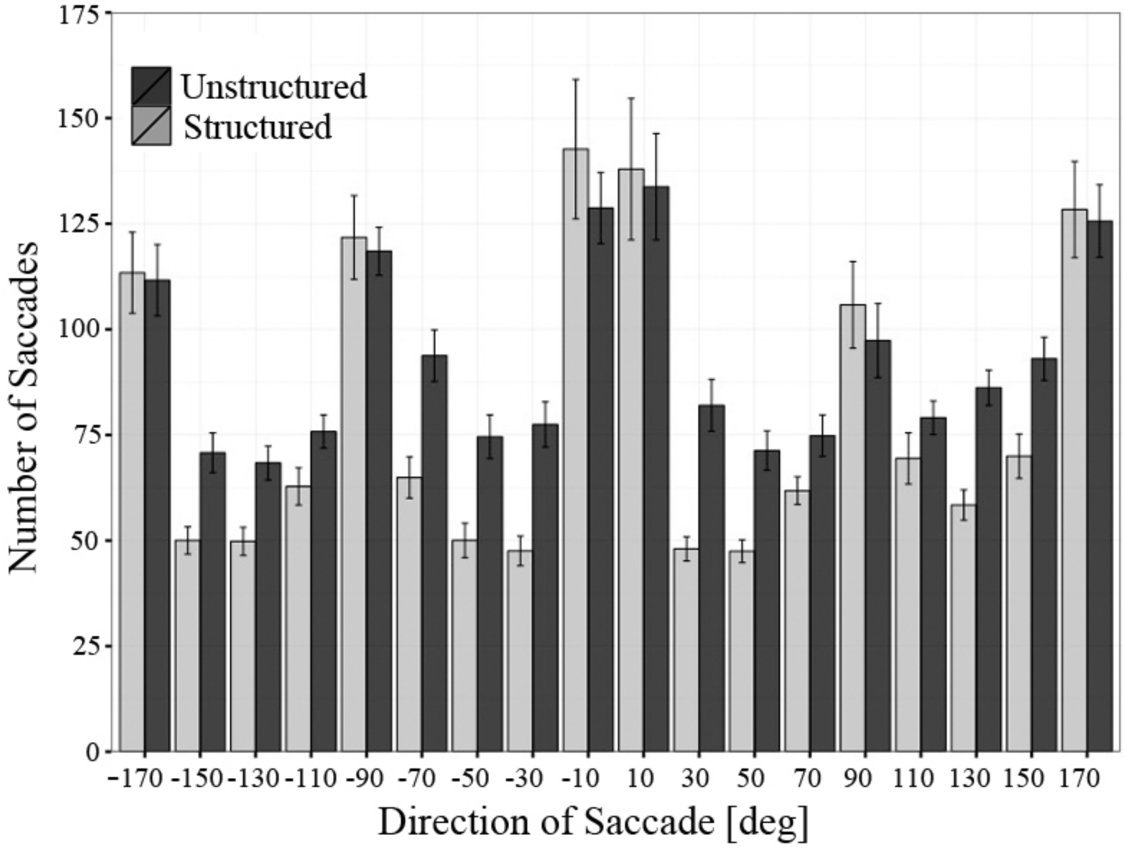


Figure 5, *Bar graph plotting the frequency of saccades in each given direction bin between structured and unstructured trials including error bars indicating 2 standard errors*

Saccade peak velocities over time

In order to investigate changes in saccade peak velocities over time, we first ran two models one for target present and one for target absent trials. In constructing models, cognitive load, structure, trial number, block number saccade number and saccade amplitude were entered as fixed effects whereas subjects were entered as random effects. As model comparisons for all fixed effects and their interactions would have been unnecessarily time-consuming, significance values were interpreted by means of the *t*-statistic. Given the large amount of observations for each participant the *t*-statistic (i.e. the Average Effect Size / Standard error) effectively corresponds to the *z*-statistic (Kliegl et al., 2013). Effects larger than twice their standard errors were interpreted as significant beyond the 5% level (*t*-value => 2). Previous analyses had shown that more fixations (and therefore also saccades) were being made in the high compared to the low as well as the unstructured compared to the structured condition. Furthermore saccade peak velocities have been shown to decrease as a function of time on task (DiStasi, 2012). The fact that more eye movements were being made in some conditions would have affected over-time analyses of peak velocities. Therefore prior to constructing LMMs, the data were reduced to the first 20 saccades in each trial. We were primarily interested in the effects of over time measures such as saccade number, trial number and block number as well as the interaction of structure and cognitive load with these variables. In the following section all significant effects are reported.

When the target was present saccade peak velocities increased as a function of saccade amplitude (*b*= 46.83; *SE*= .15; t= 311.08). There was however no main effect of structure (*b*= -.83; *SE*= 5.84; *t*= -.14); load (*b*= 3.58; *SE*= 5.85; *t*= .61), trial number (*b*= .005; *SE*= .03; *t*= .02), block number (*b*= .33; *SE*= .25; *t*= 1.31) or saccade number (*b*= -.21; *SE*= .39; *t*= -.53) on saccade peak velocities. Furthermore we found a three-way interaction between structure, trial number and saccade number (*b*= -.25; *SE*= .09; *t*= -2.81).

When the target was absent saccade peak velocities increased as a function of saccade amplitude (*b*= 44.32; *SE*= 0.11; *t*= 386.9) and decreased over blocks (*b*= .49; *SE*= .22; *t*= 2.3). There was however no main effect of structure (*b*= 3.76; *SE*= 5.08; *t*= .7), load (*b*= -4.38; *SE*= 5.08; *t*= -.9), trial number (*b*= .2; *SE*= .3; *t*= .7) or saccade number (*b*= .12; *SE*= .26; *t*= .5) on saccade peak velocities. We found significant interactions between structure and block number (*b*= -.89; *SE*= .43; *t*= -2.1), structure and saccade number (*b*= -1.05; *SE*= .52; *t*= -2), load and saccade number (*b*= 1.13; *SE*= .43; *t*= 2.6), block number and saccade number (*b*= -.06; *SE*= .02; *t*= -2.7).

Furthermore results indicated a three-way interaction between load, trial number and block number (*b*= -.12; *SE*= .05; *t*= -2.1) as well as a three-way interaction between load, block number and saccade number (*b*= -.13; *SE*= .046; *t*= -2.9),

In order to explore the effects of our "time" measures in isolation, further models were constructed with structure, load and saccade amplitude as well as either saccade number, trial number or block number as fixed effects as well as subject as a random effect. When the target was present, a model with block number as fixed effects showed significant main effects of structure (*b*= -8.38; *SE*= 2.92; *t*= -2.86), saccade amplitude (*b*= 46.02; *SE*= .31; *t*= 149.38), and block number (*b*= -5.06; *SE*= .13; *t*= -4.03) on saccade amplitudes. Furthermore results indicated a significant interaction between structure and load (*b*= .22; *SE*= 5.86; *t*= 3.86), load and saccade amplitude (*b*= 1.85; *SE*= .65; *t*= 3.02), saccade amplitude and block number (*b*= .08; *SE*= .02; *t*= 3.06). Furthermore we found a significant three-way interaction between structure, load and saccade amplitude (*b*= -6.13; *SE*= 1.23; *t*= -4.98), structure, load and block number (*b*= -1.82; *SE*= .51; *t*= -3.6) as well as a four-way interaction between structure, load, saccade amplitude and block number (*b*= .46; *SE*= .12; *t*= 4.32).

A model with trial number as the time measure in the fixed effect term showed a significant main effect of structure (*b*= -7.37; *SE*= 2.95; *t*= -2.5), load (*b*= -7.02; *SE*= 2.94; *t*= -2.38), saccade amplitude (*b*= 45.77; *SE*= .31; *t*= 147.96) and trial number (*b*= -0.77; *SE*= .18; *t*= -4.36), on saccade peak velocities. Furthermore we found significant interactions between structure and saccade amplitude (*b*= 1.43; *SE*= .62; *t*= 2.31), load and saccade amplitude (*b*= 3.38; *SE*= .62; *t*= 5.47), load and trial number (*b*= .82; *SE*= .36; *t*= 2.33), saccade amplitude and trial number (*b*= .15; *SE*= .037; *t*= 4.12), structure load and saccade amplitude (*b*= -3.59; *SE*= 1.24; *t*= -2.9), load, saccade amplitude and trial number (*b*= -.22; *SE*= .07; *t*= -2.92) as well as structure, load, saccade amplitude and trial number (*b*= .3; *SE*= .15; *t*= 2.05). A model with saccade number as the time measure in the fixed effect term indicated significant main effects of saccade amplitude (*b*= 51.28; *SE*= .28; *t*= 181.85) and saccade number (*b*= 2.02; *SE*= .17; *t*= 12.21). Furthermore we found interactions between structure and load (*b*= -11.31; *SE*= 4.99; *t*= -2.27), structure and saccade amplitude (*b*= -1.8; *SE*= .56; *t*= -3.24), structure and saccade number (*b*= -2.12; *SE*= .33; *t*= -6.48), saccade amplitude and saccade number (*b*= -.62; *SE*= .03; *t*= -18.05), structure load and amplitude (*b*= 2.41; *SE*= 1.12; *t*= 2.16), structure, load and saccade number (*b*= 1.39; *SE*= .65; *t*= 2.14), structure, amplitude and saccade number (*b*= .45; *SE*= .069; *t*= 6.5) as well as structure load saccade amplitude and saccade number (*b*= -.4; *SE*= .13; *t*= -2.88). Changes in average SPVs for target present trials between high and low cognitive load conditions can be seen as a function of saccade number in Figure 6, trial number in Figure 7 and block number in Figure 8.

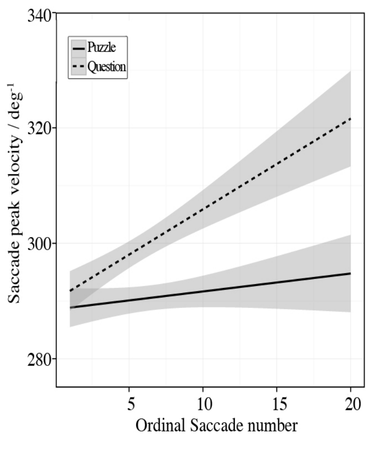


***Figure 6,** Saccade Peak Velocities as a function of saccade number for high and low load conditions when the target was present.*

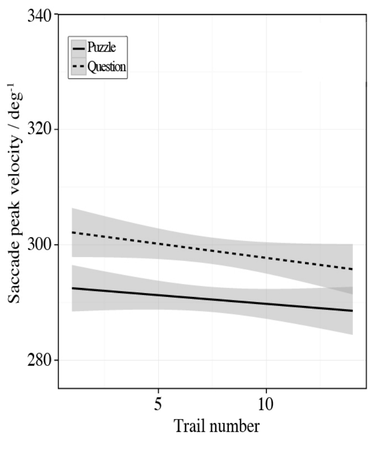


***Figure 7,** Saccade Peak Velocities as a function of trial number for high and low load conditions when the target was present.*

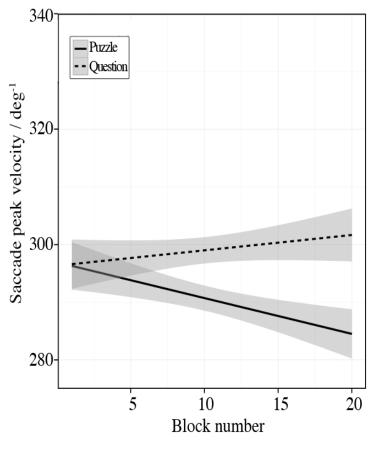


***Figure 8,** Saccade Peak Velocities as a function of block number for high and low load conditions when the target was present.*

When the target was absent a model with block number as the time measures in the fixed effect term indicated significant main effects of structure (*b*= -24.9; *SE*= 2.38; *t*= -10.45), saccade amplitude (*b*= 43.32; *SE*= .23; *t*= 187.63) and block number (*b*= -.48; *SE*= .1; *t*= -4.66). Furthermore we found significant interactions between structure and load (*b*= 25.11; *SE*= 4.77; *t*= 5.26), structure and saccade amplitude (*b*= 5.21; *SE*= .46; *t*= 11.3), load and saccade amplitude (*b*= 1.6; *SE*= .46; *t*= 3.47), structure and block number (*b*= .83; *SE*= .21; *t*= 4.04), saccade amplitude and block number (*b*= .083; *SE*= .02; *t*= 4.19), structure, load and saccade amplitude (*b*= -5.91; *SE*= .92; *t*= -6.41), structure, load and block number (*b*= -3.03; *SE*= .41; *t*= -7.35), structure, saccade amplitude and block number (*b*= -.25; *SE*= .04; *t*= -6.29), load, saccade amplitude and block number (*b*= -.088; *SE*= .04; *t*= -2.23) as well as structure, load, saccade amplitude and block number (*b*= .55; *SE*= .079; *t*= 6.91).

When trial number was entered as the time measure in the fixed effect term results showed a significant main effect of structure (*b*= -20.38; *SE*= 2.44; *t*= -8.36), saccade amplitude (*b*= 43.56; *SE*= .23; *t*= 186.09) and trial number (*b*= -.56; *SE*= .14; *t*= -3.85). We also found significant interactions between structure and saccade amplitude (*b*= 2.83; *SE*= .47; *t*= 6.06), saccade amplitude and trial number (*b*= .081; *SE*= .028; *t*= 2.9), structure, load and saccade amplitude (*b*= -2.22; *SE*= .93; *t*= -2.37) as well as structure, load, saccade amplitude and trial number (*b*= .25; *SE*= .11; *t*= 2.26).

When saccade number was entered as the time measure in the fixed effect term the model indicated main effects of structure (*b*= -12.25; *SE*= 2.27; *t*= -5.39), saccade amplitude (*b*= 47.82; *SE*= .24; *t*= 203.02), and saccade number (*b*= 1.44; *SE*= .12; *t*= 11.81). Furthermore we found significant interactions between structure and load (*b*= -14.38; *SE*= 4.55; *t*= -3.16), structure and saccade amplitude (*b*= 2.53; *SE*= .47; *t*= 5.39), load and saccade amplitude (*b*= 1.41; *SE*= .47; *t*= 5.39), structure and saccade number (*b*= -.64; *SE*= .24; *t*= -2.65), load and saccade number (*b*= 1.07; *SE*= .24; *t*=

4.41), saccade amplitude and saccade number (*b*= -.43; *SE*= .024; *t*= -17.63), load, saccade amplitude and saccade number (*b*= -.12; *SE*= .05; *t*= -2.57) as well as structure, load saccade amplitude and saccade number (*b*= -.23; *SE*= .096; *t*= -2.36). Changes in average SPVs between high and low cognitive task demand conditions can be seen as a function of saccade number in Figure 9, trial number in Figure 10 and block number in Figure 11.

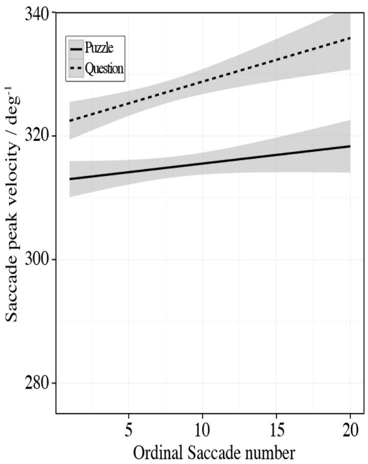


Figure 9, *Saccade Peak Velocities as a function of saccade number for high and low load conditions when the target was absent.*

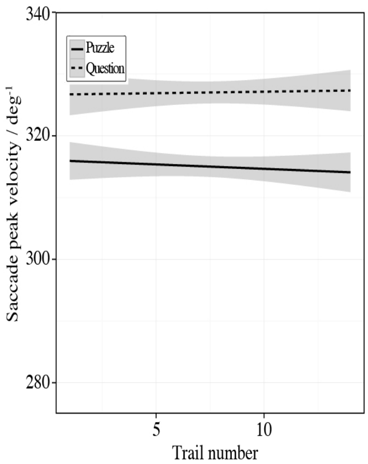


Figure 10, *Saccade Peak Velocities as a function of trial number for high and low load conditions when the target was absent.*

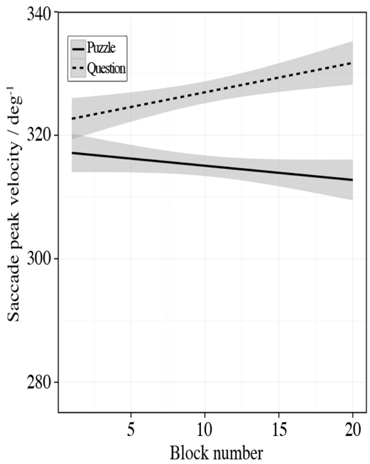


Figure 11, *Saccade Peak Velocities as a function of block number for high and low load conditions when the target was absent.*

Discussion

In the current experiment we considered the consequences of contemplating a previously heard puzzle on behavioural and oculomotor measures within a low-level visual search task. We were interested in 1) determining the extent to which systematic components (Gilchrist & Harvey, 2006) of visual search were affected by secondary cognitive task demand; and 2) whether previously observed decrements in hazard perception performance (Savage, Potter & Tatler, 2013) may, to some extent, be related to cognitive load interfering with processes of visual search.

The effects of array structure on visual search

The organization of information in the search array changed how people viewed these arrays. Specifically, when searching a structured array, fewer fixations and re-fixations were made of items than in the unstructured array, although the former was only true in trials in which the target was present. In target absent trials there was an additional effect upon saccade durations, with shorter duration saccades when searching unstructured arrays than when searching structured arrays. Array structure did not influence search times, but when searching arrays containing a target, participants made more false responses (erroneously indicating that no target was present) in structured arrays and were also slower to verify the fixated targets within unstructured arrays.

The disruption of the display structure resulted in a modulation of systematic scanning. In highly regular grids the distribution of saccade directions was different than in irregular grids. Although the structure of the array affected the overall distribution of fixations, participant still exhibited a systematic element in visual scanning, which was best described as making significantly more horizontal than vertical saccades. Similarly to previous research this current study confirms that the disruption of the regular grid like structure altered this strategic element within saccade distributions but did not eliminate it (Gilchrist & Harvey, 2006). This suggests that systematic scanning of visual scenes does not necessarily rely on strictly regular displays. Work by Tatler & Vincent (2009) has shown that when viewing complex scenes, horizontal and vertical saccade directions are more common than oblique saccades. Most natural scenes contain a complex spatial structure (Marr, 1982), which most likely shape systematic scanning. Furthermore subjects systematically search around circular displays, which indicates that systematic scanning is not unique to regular grid-like displays (Hooge, & Erkelens, 1996) but can be influenced strongly by the structure of the array.

Whereas overall RTs were not affected by the structure of the array, participants made significantly more refixations in unstructured as compared to structured arrays both when the target was absent along with significantly more fixations when the target was present. Previous research has shown that the structure of the array can influence search efficiency (Simonin, Kieffer & Carbonell, 2005). Elliptic displays have been associated with shorter scan paths and search times in comparison to matrix layouts. However as in the current experiment there was no difference in terms of search times between structured and unstructured arrays. This may be due to the fact that we altered the consistency of a grid like display rather than changing the structure altogether.

The effect of cognitive load in visual search

Secondary cognitive task demand influenced subjects' search behaviour. In both target present and absent trials, increased cognitive load resulted in longer RTs and VTs, more fixations and refixations, longer fixation durations and first saccade latencies and slower overall saccade peak velocities. In addition to this when the target was not present, participants' response performance was significantly worse and the spread of fixations reduced along the x-axis when secondary cognitive task demand was high.

Previous research has demonstrated that additional secondary cognitive load increased response times in visual search tasks (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). Depending on the nature of secondary memory task and the primary search stimuli, cognitive load has in some cases been shown to influence the slope of the search function (Oh & Kim, 2004; Woodman & Luck, 2004).

However other work (Woodman et al., 2001) has suggested that although secondary cognitive task demand lead to a general increase in search times, it did not influence the efficiency of the search itself (i.e. the slope of the search function is not affected). Although visual search is typically thought to require working memory resources (Bundesen, 1990; Duncan & Humphreys, 1989) these results have been taken to indicate that the cost to response times under load was caused by interference to processes either prior to (e.g. residual encoding processes) or following (e.g. response generation) the search itself. As the current study tracked participants' eye movements while they searched, we were able to determine which processes of search were influenced by secondary cognitive load.

In pro- and antisaccade tasks first saccade latencies were shorter when the onset of the target was preceded by an alerting signal (e.g., Lorenz, Oonk, Barnes, & Hughes, 1995**).** In Experiment I of this thesis we demonstrated that distraction lead to an increase in first saccade latencies, indicating that processes relating to alerting and / or preparation were to some extent disrupted. In the current Experiment, first saccade latencies were significantly longer, indicating that processes prior to the start of the overt search activity were affected by cognitive load. During visual search, fixation durations were significantly longer, the number of fixations and refixations were greater and therefore time to hit the target was increased. This indicated that cognitive task demand might have been affecting search efficiency. Finally VTs, which was the time measured between the final fixation upon the target and the following manual button response, were significantly longer in the high compared to the low cognitive load condition. This demonstrated that processes following the search were also being affected. The current study therefore implies that observed slowing down of RTs in visual search trials under load was due to secondary cognitive task demand interfering with multiple stages of search: 1) prior to (initial encoding); 2) during search; and 3) after the search itself (response selection).

An important consideration is not just how long people take to find the target, but also the time it takes to terminate visual search when no target is present (Chun & Wolfe, 1996). In the current study, in addition to taking longer to find the target when one was present, participants searched for longer until reaching a target absent decision when secondary cognitive load was high. This was associated with an increase in the number of fixations and refixations when participants were preoccupied with the secondary task and no target was present. Two strategies have been put forward for deciding that the target was not present without searching the entire display: 1) participants may only search through those items which have the highest likelihood of being the target and ignore all others; 2) subjects might develop a rough estimate of how long it takes to find the target on present trials. Using this estimate participants are thought to be able to inform "educated guesses" as to how long they "should" take to find the target (Chun & Wolfe, 1996). In the current study participants were not just slower at reaching a target absent decision, they were also significantly worse in reaching a correct target absent decision. From simulated driving research we know subjects compensate for increases in secondary cognitive task demand by reducing driving speeds (Patten et al., 2004). The fact that subjects searched for longer when distracted and no target was present may reflect a similar compensatory strategy. In future, analysing changes in correct target absent decision times over time between high and low load conditions may reveal to what extent cognitive load interferes with heuristic strategies (or forming "educated guesses"). As in the current experiment the target was an upward amongst leftward and downward facing triangles it cannot be said that any one distractor was more likely to be the target than the other. It could be argued that the salience between distractors was very likely to be the same and that therefore no guidance could have occurred during search (Wolfe, 1994), thus resulting in more distractors being inspected. Furthermore when the target was absent and cognitive load was high, participants made significantly more fixations and refixations as well as exhibited longer fixation durations. This would have undoubtedly contributed to an increase in RTs in target absent trials. Interestingly, although people took more time to reach a decision they were no more (or less) accurate in terms of their final motor responses. When cognitive load was high, participants were significantly worse at reaching a target absent decision. In target present trials, subjects exhibited longer VTs, which may have indicated an interference with response selection and decision-making processes once participants had fixated upon the target item. As time to hit and VTs could only be calculated in trials where a target was actually present, we argue that increased false responses in target absent trials reflected differences in processes after the termination of visual search.

As Shore and Klein (2000) have demonstrated, memory processes can have an effect on visual search at a variety of levels. One issue that remains to be determined is the extent to which memory mechanisms are necessary to prevent the re-fixating of previously inspected items. Previous research has argued a range of positions including that memory plays no role (Horowitz & Wolfe, 1998), a limited role (Gilchrist & Harvey, 2000) and even an extensive role (Peterson et al., 2001) in preventing re-fixations. Results from this current study indicated that when secondary cognitive task demand was high, participants' total number of fixations and refixations was significantly greater. This seems to indicate that increases in higher-level executive functions such as working memory are required for the processing and storage of distractor locations.

Fixation durations were significantly longer in the high compared to the low cognitive load condition. The combination of more fixations and longer fixation durations in the high load condition may be the cause of the observed increases in time to hit the target (on target present trials) and RTs in both target present and absent trials. Fixation durations have been associated with processing demands. In reading studies fixation durations on infrequent words are longer than frequent words (Rayner, 1998). In real world tasks fixation durations depend on the time required to extract the necessary information from any particular activity (Droll, Hayhoe, Triesch & Sulllivan, 2005; Hayhoe et al., 2003). Fixation durations have also been shown to be longer when the luminance (Loftus, 1985) or contrast (Loftus et al., 1992) of fixated items was reduced (Van Diepen et al., 1995). Furthermore fixation durations are longer on full colour photographs in comparison to black and white line drawings with similar distribution of visual information (Henderson & Hollingworth, 1998). This indicates that fixation durations are influenced by the effort involved in extracting visual information from any given fixated location, longer fixation durations being related to more effortful information extraction. Therefore in the current experiment, longer fixation durations in the high cognitive load condition may suggest a cross modal interference with visual processing thus resulting in more time being needed to extract the necessary information from any given fixation. The dissociation between the effects of structure and cognitive load on fixation durations may indicate that as long as the amount of visual information is constant that the structure of this visual scene does not influence how quickly we are able to extract the necessary information.

The strategic component of visual search as descried by Gilchrist and Harvey (2006) was not just affected by the structure of the array, but also by secondary cognitive task demand. Although results demonstrated overall more fixations in the high compared to the low load condition, the distribution of saccade directions indicated that preoccupation was to some extent altering how saccades were directed from saccade to saccade. Changes in the distribution of fixations as a result of increased cognitive task demand were exhibited by a marginally significant reduction in the spread of fixations along the x-axis when the target was absent. This current study demonstrated that increases in secondary cognitive task demand resulted in 1) a change in the direction distribution of saccades and 2) a reduction of the spread of fixations along the horizontal axis when the target was absent.

Changes to different elements of eye blinks have been seen as indicators of both visual and mental workload as well as fatigue. Increases in visual task demand such as the complexity of the array has been shown to result in a decrease in blink durations (Ahlstrohm & Friendman-Berg, 2006) whereas increases in secondary cognitive task demand have been shown to lead to an increase in blink rates (Benedetto et al., 2011; Savage, Potter & Tatler, 2013). Evidence from real-life driving studies (Recarte & Nunes, 2002) has supported the dissociation of visual and cognitive task demand on blink rates and durations. High secondary cognitive load resulted in more frequent blinks and increases in visual load led to shorter blink durations. It has been argued that increases in visual task demand result in a blink inhibition effect (Stern et al., 1994). However increased cognitive load has been thought to interfere with such inhibitory control processes, thus resulting in higher blink rates. In line with previous research, the current study demonstrated that blink rates were significantly higher when cognitive load was high.

Research by Savage, Potter and Tatler (2013) showed a significant increase in overall saccade peak velocities as a result of increased cognitive load. An increase in traffic density has been associated with slower peak velocities (DiStasi et al., 2010). In this current study we found no effect of cognitive load on participants' first saccade peak velocity. However when the first 20 saccades were analysed results demonstrated that peak velocities were significantly slower in the high compared to the low cognitive load condition. As visual information density was not manipulated (i.e. by increasing number of distractors) this result seems to contradict previous findings by Savage et al (2013). However it should be noted that peak velocities decreased significantly over time in the high but not in the low cognitive load condition. Therefore the decrease in velocities occurring over time in one condition (and not the other) most likely resulted in the significant difference in overall peak velocities.

Previous research has demonstrated that peak velocities decrease as a function of time on task (Galley, 1993; DiStasi, 2012). Over the course of the experiment in both target present and absent trials, saccade peak velocities remained constant in the low and decrease in the high cognitive task demand condition, indicating that time on task alone was not the only factor affecting saccade peak velocities. This pattern was consistent with a mental fatigue account of changes in saccade peak velocities (DiStasi et al., 2011), which postulates that saccade peak velocities decrease as a function of metal fatigue. It could be argued that as the high cognitive task demand condition is more mentally fatiguing saccade peak velocities decrease over the course of the experiment.

Conclusions

Results from this current study indicated that processes prior to, during and following visual search were all negatively affected by secondary cognitive task demand. Prior to the beginning of visual search itself, first saccade latencies were significantly increased when cognitive load was high. During the actual task of searching for a target, fixations and refixations were more frequent and fixation durations were longer, which resulted in a longer time taken to find the target when secondary load was high. Finally, once the target had been fixated upon subjects required longer to generate a manual response, which may have indicated that processes following visual search such as response selection were being affected by cognitive distraction. Increases in false responses when the target was absent suggested that participants were significantly worse at reaching a target absent decision when cognitive load was high. Furthermore the introduction of a secondary cognitive task resulted in a change in the distribution of fixations and saccade directions. Taken together results from this current experiment may indicate that the deficits resulting from increases in secondary cognitive load, previously observed in a hazard perception paradigm, may be in part due to cognitive load interfering with processes of visual search.

The first two chapters of this thesis considered the effect of secondary cognitive task demand on individual component processes vital to good hazard perception performance. We have isolated processes of alerting, orienting, inhibitory control and visual search in well established primary tasks and have demonstrated that distraction leads to a disruption of all four mechanisms. The aim of the following chapter is to isolate the individual component processes of secondary conversation tasks, namely: working memory, language processing and language production; and to determine their effects on primary hazard perception performance.

Chapter IV

Comparing the effects of working memory, processing and producing verbal information on hazard perception performance

Introduction

Previous chapters of this thesis were aimed at isolating individual component processes of the primary hazard perception task such as orienting, inhibitory control and visual search; and examining their susceptibility to increases in cognitive load. The three experiments of this current chapter were aimed at isolating individual component processes that may be involved in conversing on a mobile phone and evaluating their effects on hazard perception performance as well as evaluating an alternative to puzzle solving as a means of preoccupation.

Conversing on the telephone whilst driving has been shown to negatively affect a wide variety of different measures on a series of different driving tasks (Haigney et al., 2000; Strayer, Drews, Albert & Johnston, 2003; Törnros & Bolling, 2005). There is also increasing evidence indicating that conversing on a hands-free device has detrimental effects on driving performance (Lamble, Kauranen, Laakso & Summala, 1999; Strayer & Johston, 2001, Patten Kircher, Östlund & Nilsson, 2004). Therefore the distraction caused by telephoning is in no small part due to the increase in cognitive task demand associated with conversing. Furthermore, results have indicated that the distraction caused by telephoning whilst driving may not be limited to the period of the conversation itself (Haigney & Taylor, 1998; Redelmeier & Tibshirani, 1997).

Conversing on a mobile phone requires a variety of component sub processes such as processing verbal information (listening), working memory and language production (speaking). Memory for conversations clearly incorporates a large variety of different types of memory such as semantic and contextual memory. However, by examining the effect of the individual component processes (of the more complex conversation task) on hazard perception performance it may be possible to determine which element of conversing on a mobile phone interferes most with hazard perception.

To this effect the current chapter was aimed at contrasting three different secondary tasks to assess the effects of (1) working memory; (2) working memory and auditory processing (3) working memory, auditory processing and language production on hazard perception performance. Real conversations are difficult to control in terms of content, however more importantly given the individual differences in the perceived importance, personal importance as well as higher-level cognitive processes such as contextual and semantic memory **(**Ley, 1978; Conway & Bekerian, 1987; Stafford, Burggraf & Sharkey, 1987**)** the effect of load would vary too greatly from person to person. Given that our aim is to understand the effects of cognitive load on hazard perception performance we required a more controlled and consistent secondary cognitive task. To avoid any variation in working memory load, wordlists (balanced for word length and frequency) consisting of 15 words were created from established wordlist tasks (Lezak, 2004; see appendix). The onset of the secondary wordlist task as well as the task instructions were varied across three experiments to isolate the above mentioned component processes and their effects on hazard perception performance were compared. 1) Working memory was isolated by presenting the secondary wordlist task prior to the onset of the hazard perception task and instructing participants to rehearse during the primary task and recall as many words as possible at the end of each 1-minute clip. 2) The combined processes of working memory and auditory information processing were examined by presenting the secondary wordlist task at the same time as the primary hazard perception task and instructing participants to recall as many words as possible at the end of each 1-minute clip. 3) Combined processes of working memory, processing auditory and producing verbal information were examined by means of a modified n-back1 task with words instead of numbers, which participants were required to complete concurrently with the primary hazard perception task. For a review of the various working memory load tasks see Purves et al. (2008) and Lezak et al. (2004).

The n-back task typically requires subjects to report when an item in a serially presented list matches the item "n" steps back in the list. It has been argued that working memory is necessary to maintain previously presented items in mind whilst attending to the current item (Lezak, 2004). Higher-level executive functions such as decision making and monitoring are thought to play a role in the active comparison of the current with the n^{th} item. The variant of the n-back task utilized in the current experiment involved listening to a list of items and stating out loud the n^{th} item back from the one that was currently presented. This particular variation of the n-back task is thought (to some extent) to isolate working memory components from decision-making, monitoring and response selection mechanisms involved in comparing the current and the n^{th} item (Lezak, 2004).

Each of the three secondary tasks in this current study was designed to isolate a specific component process involved in conversing. Comparing hazard perception performance across these three secondary tasks may demonstrate which aspect of conversing is most detrimental to primary task performance. Primary task performance in all three experiments was assessed between high and low cognitive load conditions. Cognitive load was considered high on either wordlist or n-back1 trials and low on trials in which participants had been presented a simple question (i.e. Q: "*Which city are you currently in?*") prior to the start of each hazard perception clip (see appendix for list of simple questions).

The most commonly utilized measures of driving performance across all driving tasks are RTs and missing responses to hazardous events as well as false responses to potential hazards (Irwin, Fitzgerald & Berg, 2000; Hancock, Lesch & Simmons, 2003; Patten et al., 2004). Typically it has been shown that telephoning and driving resulted in slower reaction times to hazardous stimuli (Strayer & Drews, 2004), impaired situational awareness (Kass, Cole & Stanny, 2007), gap judgement (Bowditch, 2001), steering behaviour (Rakauskas, Gugerty & Ward, 2004) and sensitivity to road conditions (Haigney, Taylor & Westermann, 2000). In hazard perception, distraction of any kind leads to increased RTs as well as missing responses, although there is some evidence that FRs are also affected (Savage et al., 2013). In this current series of experiments, hazard perception performance was assessed by means of RTs and number of correct detections of hazardous events as well as FRs to non-hazardous events. Although FRs to non-hazardous events may not necessarily be detrimental in real-life driving situations, erroneously responding to non-hazardous events may to some extent reflect the efficiency of visual processing (or lack thereof) within the primary hazard perception task.

It is important to note that each experiment utilized the same wordlists and simple questions as well as hazard perception clips. First, the effect of each secondary task was compared to a control condition by means of pairwise analyses in order to confirm that all of the secondary tasks caused a significant impairment in hazard perception performance compared to the low load condition. The data were then analysed across experiments by means of a mixed design ANOVA with low vs. high cognitive load as a within-subjects factor and the type of secondary cognitive task as between-subjects factors. The magnitude of the effect of the secondary task on hazard perception performance may indicate which component process of conversation most impairs primary task performance.

Finally, participants' digit span and performance on the secondary working memory load task were each correlated with hazard perception performance on high load trials. This was done for two reasons: 1) given the correlation between working memory load and digit span performance, it could be reasoned that individuals with high digit spans are able to more effectively compute both tasks simultaneously in comparison to subjects with low digit spans. Therefore, examining the relationship between digit span and RTs, FRs and Hits may provide an indication whether or not this is the case. 2) Previous research has indicated that participants are able to prioritize one task over another depending on the current demands of each task (Strayer et al., 2001). In their simulator study, driving performance was only affected by a secondary working memory task when the primary task was easy. The authors argued that when the primary task was sufficiently simple, attention resources were allocated to the secondary task resulting in decreased performance in the driving task. Therefore, examining the relationship between secondary (working memory) task performance and (primary) hazard perception may provide some insight into whether participants were prioritizing one task over the other.

Methods

Design

Three within subjects design experiments were conducted. In each experiment the independent variable was the level of cognitive task demand, which could either be high or low. In Experiment 1, cognitive load was considered high on trials in which participants were required to remember a list of 15 words that were presented directly prior to the start of each hazard perception movie. In Experiment 2, cognitive task demand was considered high on trials in which participants were required to listen to and remember as many words as possible from a 15-item list whilst simultaneously performing the hazard perception task. Finally, in Experiment 3 cognitive task demand was considered high on trials in which participants were required to perform a verbal n-back1 task (with words instead of numbers) during the hazard perception task. Cognitive task demand in all three experiments was considered to be low on trials in which participants had been posed a simple question (i.e.: "*What city are you currently in*?") directly prior to the start of the hazard perception clip. The dependent variables were RTs and total hits to hazardous events as well as FRs to non-hazardous events.

Participants

For each of the three experiments, a sample of 20 Participants, 10 male and 10 female, were recruited via the Universities Research Participation System "SONA". Participants were required to be between the ages of 18 and 24 and to be in possession of a DVLA approved driving licence. According to a self reported estimate, participant's driving frequency ranged between once and seven times weekly with no subject driving less than once a week. Some of the participant data for Experiments 1 and 2 were collected as part of a collaboration between 5 undergraduate students, all exploring different questions relating to a commonly developed paradigm. In total 60 participants (30 male and 30 female) were recruited. Every participant in this group of studies took part in only one experiment.

Materials

Participants sat in front of a 17-inch screen on which the visual stimuli were displayed. DMDX software was used to present the video clips as well as record participants' button presses in milliseconds. We made use of 22 DVLA approved hazard perception clips, which were provided courtesy of Focus Multimedia Ltd and Imagitech Ltd. The secondary wordlist tasks as well as the control questions were presented via a set of noise cancelling headphones at a comfortable volume, which was regulated individually for each participant. Wordlists consisted of 15 items that had been balanced for word length and word frequency. Items were presented at a rate of 1 every 4 seconds resulting in a total length of 60 seconds per wordlist.

Procedure

Digit span as well as driving frequency was assessed prior to the start of testing (see appendix for digit span test as well as short driving frequency questionnaire). In the low cognitive task demand condition participants were always presented with a simple question (e.g. "*What city are you in*?") via headphones directly prior to the start of each 1-minute hazard perception clip. Wordlists were created from established wordlist tasks (Lezak, 2004)

In experiment 1, during the high cognitive task demand condition participants were presented with 15 words at a rate of one word every 4 seconds prior to the start of each hazard perception clip and were required to remember as many words from the wordlist as possible whilst performing the hazard perception task ('Wordlist Before' experiment). Recall performance was recorded at the end of each trial.

In experiment 2, the same wordlists were presented during the hazard perception clips and participants were required to listen to and rehearse as many words as possible whilst simultaneously performing the hazard perception task ('Wordlist During' experiment). Recall performance was recorded at the end of each trial.

In experiment 3, wordlists were presented simultaneously as in experiment 2, however participants were instructed to listen to and state out loud one word back from the one they had last been presented with ('Wordlist n-back1' experiment) whilst performing the hazard perception task. Participants were not required to recall any of these items from memory at the end of each trial.

During the hazard perception task, participants were instructed to be vigilant to hazardous events occurring in the video and to press a button on the response box to indicate these hazards. Each clip contained one hazard, which had been previously identified by the DVLA however participants were instructed to anticipate any number of hazards. A collection of hazard perception clips were piloted in order to determine clips which elicited a similar amount of button press responses. This was done in order to ensure that all clips used in this thesis were of similar primary task difficulty. As all participants had passed the hazard perception portion of their DVLA approved driving licence, they were familiar with what constituted a hazard within the primary task.

All responses to events that were not considered to be hazardous were classified as FRs whereas all appropriate responses to hazardous events were classified as hits. RTs to hazardous events were measured from the first frame on which the hazard appeared. Participants average RT for high and low load conditions were calculated across all the clips from each condition. RTs were measured from the first frame of the hazard appearance, as measuring from the actual onset of the hazard would have resulted in significant data loss due to subjects predicting the onset of the danger resulting from the target.

In the case of the low cognitive task demand condition, at the end of each trial participants were asked to repeat the question they had been presented with prior to the start of the hazard perception clip and to state their answer.

Each of the three experiments had a within subjects design. Participants completed 20 trials in total (10 high and 10 low load) with high and low load conditions intermixed randomly. The pairings of high and low secondary cognitive task demand and hazard perception clips were switched for one half of participants in order to counterbalance any unwanted differences in the visual information of the clips.

Analyses

Paired samples t-test within experiments

To examine whether hazard perception performance was affected by load in all the three experiments, dependent variables relating to hazard perception performance were analysed by means of paired samples t-tests.

Correlations

We were interested in determining the relationship between: 1) secondary memory task performance and hazard perception performance; and 2) participant's average digit span hazard perception performance. This was achieved by conducting a series of two-tailed bivariate correlations in order to determine the relationship between 1) memory performance on high load trials and RTs, FRs and hits on high load trials; and 2) participant's digit span and hazard perception performance on high load trials. Finally we performed a two-tailed bivariate correlation between participants prior digit span and working memory task performance.

Results

Experiment 1 – Wordlist Before

RTs to hazardous events were significantly slower in the high compared to the low cognitive task demand condition ($t\ (19) = 4.93$; $p < .01$), with participants being on average 920.35 ms slower to detect hazards in this condition. FRs to hazardous events were not significantly different between high and low task demand conditions, $t\ (19) = .29$; $p = .77$. Furthermore, average Hits on hazardous events were not affected by secondary cognitive task demand, $t\ (19) = .87$; $p = .39$.

Results indicate no significant correlations between memory performance and RTs ($r\ (18) = -.062$; $p = .8$), FRs ($r\ (18) = -.17$; $p = .47$) or Hits ($r\ (18) = -.41$; $p = .071$).

We found a significant positive correlation between digit span and RTs (r (18) = .67; *p* = .001) and a significant negative correlation between digit span and FRs (r (18) = -.53; *p*= .017) however no significant correlation between digit span and Hits (r (18) = -.36; *p*= .10). Significant correlations between digit span and RTs as well as FRs on high load trials for the secondary task 'Wordlist Before' can be seen in Figures 1 and Figure 2 respectively. Results indicate no significant correlation between the two memory performance measures (r (18) =-.02; *p*= .95).

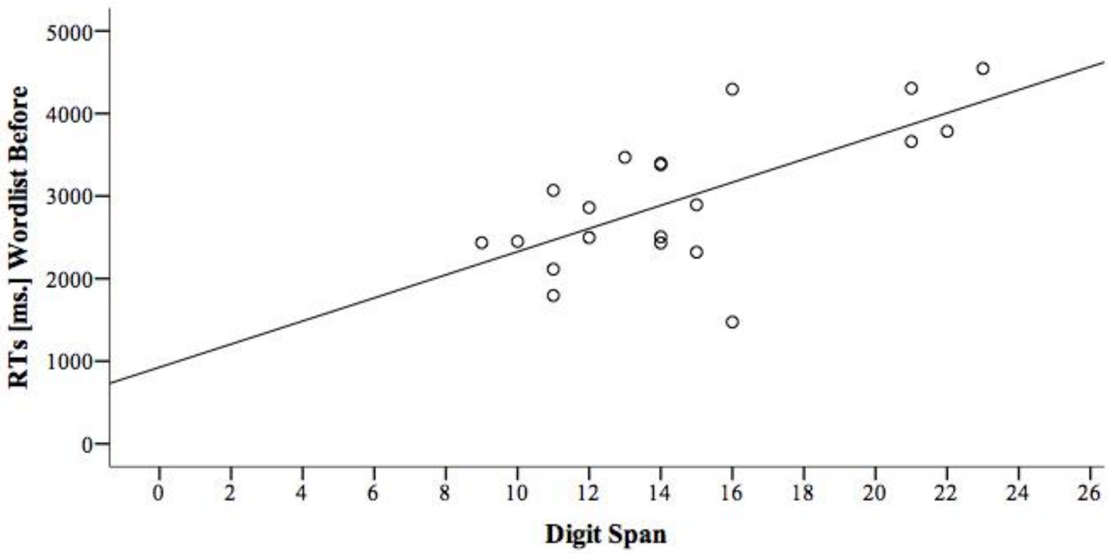


Figure 1, *Scatterplot indicating the relationship between individuals prior digit span performance and RTs in the primary task on high cognitive load trials for the secondary task 'Wordlist Before'*

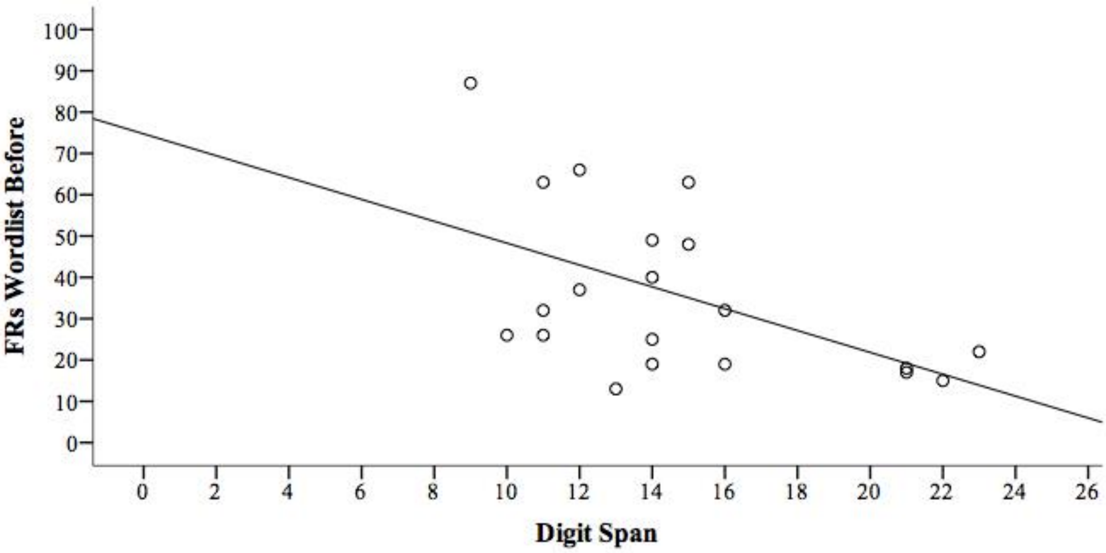


Figure 2, *Scatterplot indicating the relationship between individuals prior digit span performance and FRs to non-hazardous stimuli in the primary task on high cognitive load trials for the secondary task 'Wordlist Before'*

<u>*Experiment 2 – Wordlist During*</u>

RTs to hazardous events were significantly slower in the high compared to the low cognitive task demand condition (t = (19) = 2.65; *p*< .05), with participants being on average 452.25 ms slower to detect hazards in this condition. FRs to non-hazardous events were not significantly different between high and low task demand conditions (t (19) = 1.55; *p*= .14). Furthermore, average Hits on hazardous events were not affected by secondary cognitive task demand (t (19) = .93; *p*= .37).

We found no significant correlations between memory performance and RTs (r (18) = -.27; *p*= .25), FRs (r (18) = .06; *p*= .78) or Hits (r (18) = -.36; *p*= .12) and no significant correlations between digit span and RTs (r (18) = -.087; *p* = .72), FRs (r (18) = -.12; *p*= .66) or Hits (r (18) = -.05; *p*= .83). Furthermore, results indicated no significant correlation between the two memory performance measures (r (18) =-.24; *p*= .31).

Experiment 3 – Wordlist n-back1

RTs to hazardous events were significantly slower in the high compared to the low cognitive task demand condition (t = (19) = 5.96; *p*< .001) with participants being on average 648.2 ms slower to detect hazards in this condition. FRs to hazardous events were not significantly different between high and low task demand conditions (t (19) = 1.68; *p*= .11). Furthermore, average Hits on hazardous events were not affected by secondary cognitive task demand (t (19) = .86; *p*= .4).

There were no significant correlations between memory performance and RTs (r (18) = -.28; *p*= .24), FRs (r (18) = .28; *p*= .24) or Hits (r (18) = -.31; *p*= .18) or between digit span and RTs in high (r (18) = -.15; *p* = .54) FRs (r (18) = -.064; *p*= .79) or Hits (r (18) = -.10; *p*= .67). Finally, results indicate no significant correlation between the two memory performance measures (r (18) =-.14; *p*= .57).

3x2 mixed ANOVA across experiments

For each dependent variable, a 3 (Type of Distraction) x 2 (high vs. low cognitive load) mixed design ANOVA was carried out on the data of all three experiments. The aim was to determine whether the size of the effect of load was different between the three secondary tasks. There was a significant within-subjects effect of load on RTs (F (1, 57)=53.98; *p*<0.001) in that RTs were larger in the high compared to the low cognitive load conditions. However there was no significant within-subjects effect of cognitive load on FRs (F (1, 57)= .39; *p*= .54) and Hits (F (1, 57)= .91; *p*= .34). Furthermore results demonstrated no significant between-subjects effect of Type of Distraction ('Wordlist Before', 'Wordlist During' and 'Wordlist N-Back') on measures of RTs (F (2, 57) = .87; *p*= .43), FRs (F (2, 57)=1.01; *p*= .37) and Hits (F (2, 57)= .28; *p*= .76). This indicates that averages for high and low load conditions did not differ across Type of Distraction. Finally, there was no significant interaction between Type of Distraction and Load for RTs (F (2, 57)=2.19; *p*= .12), FRs (F (2, 57)=1.64; *p*= .2) or Hits (F (2, 57)= .41; *p*= .67). This demonstrates that the difference between high and low load conditions did not change across Type of Distraction. Average RTs, hits and false responses (FRs) for both high and low load conditions for all three Types of Distraction along with appropriate standard errors can be seen in Figure 3, 4 and 5 respectively.

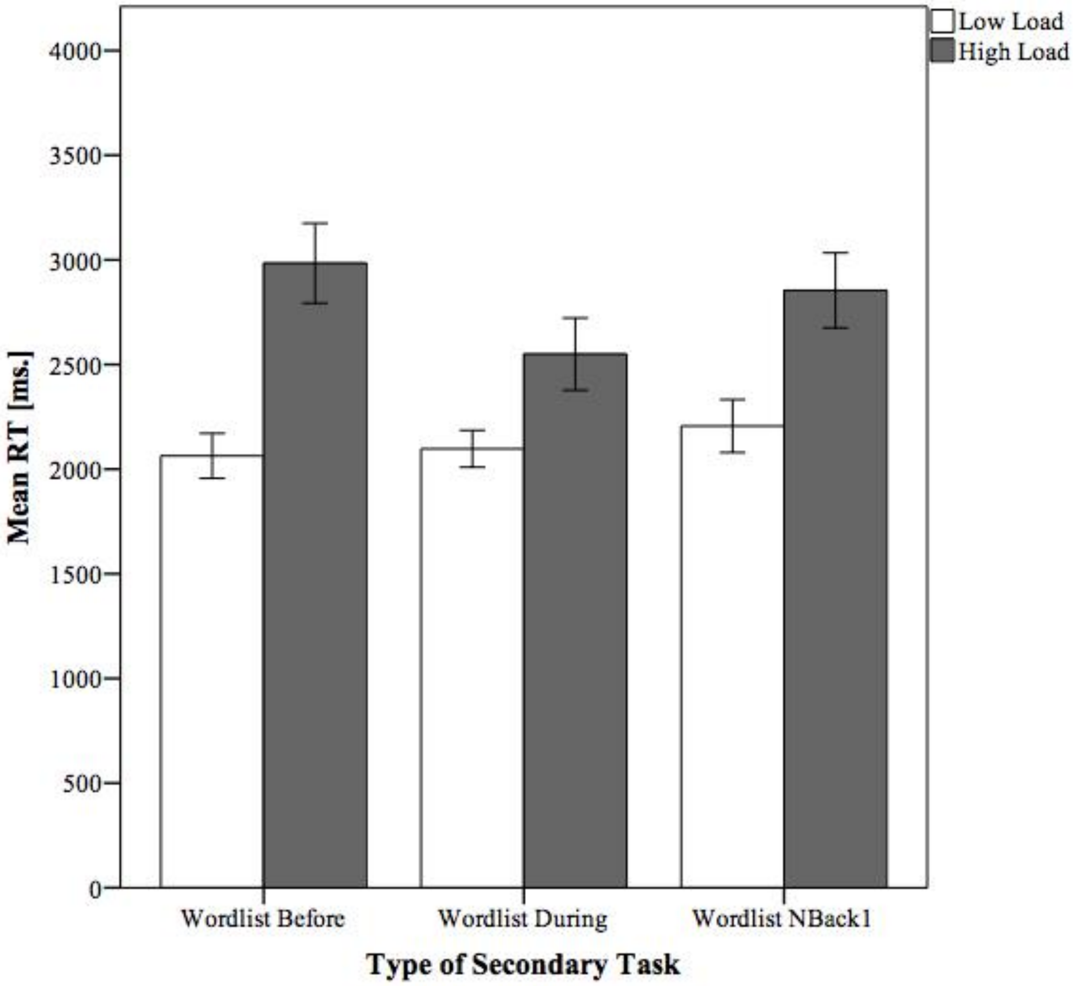


Figure 3, *Mean RTs (in milliseconds) to hazardous events in the primary task between high and low cognitive load conditions across the three different secondary tasks including error bars indicating 1 S.E.*

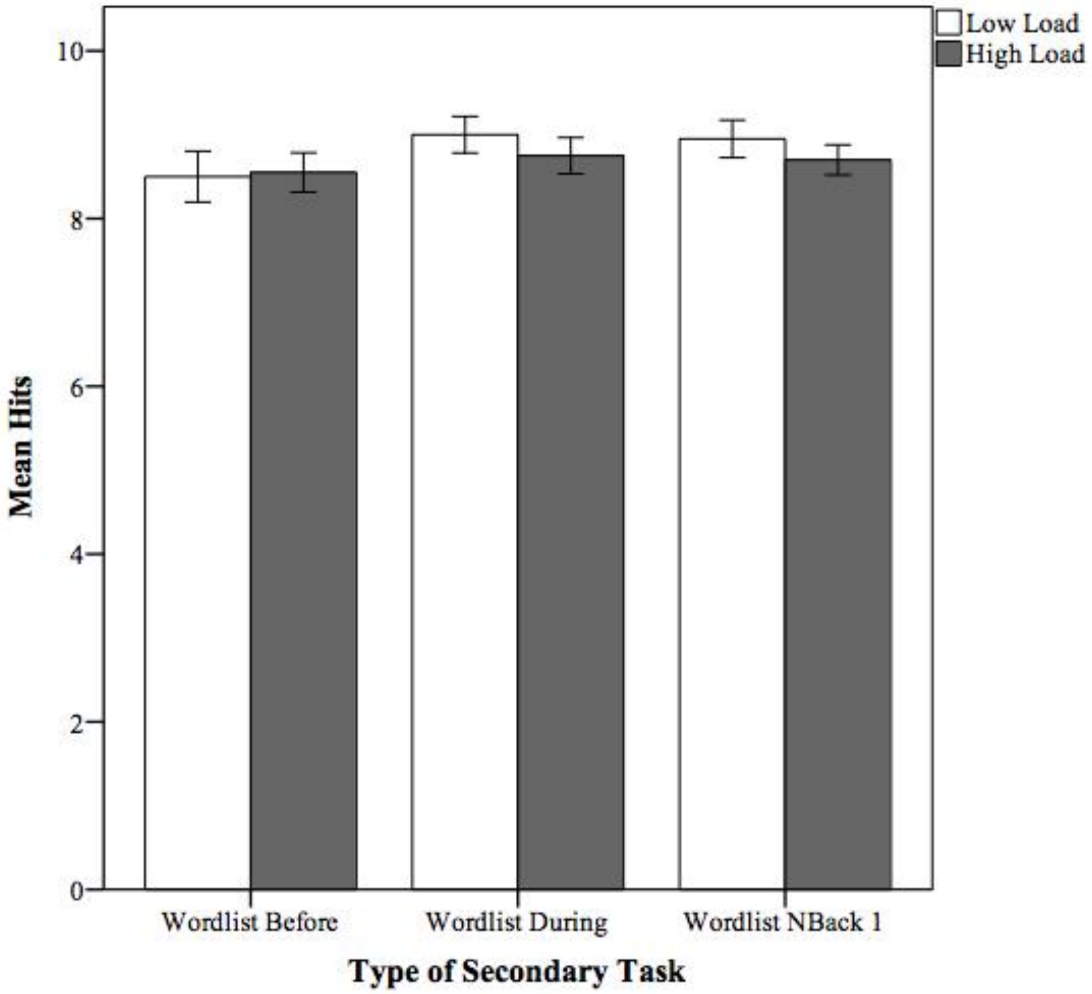


Figure 4, *Mean Hits to hazardous events in the primary task between high and low cognitive load conditions across the three different secondary tasks including error bars indicating 1 S.E.*

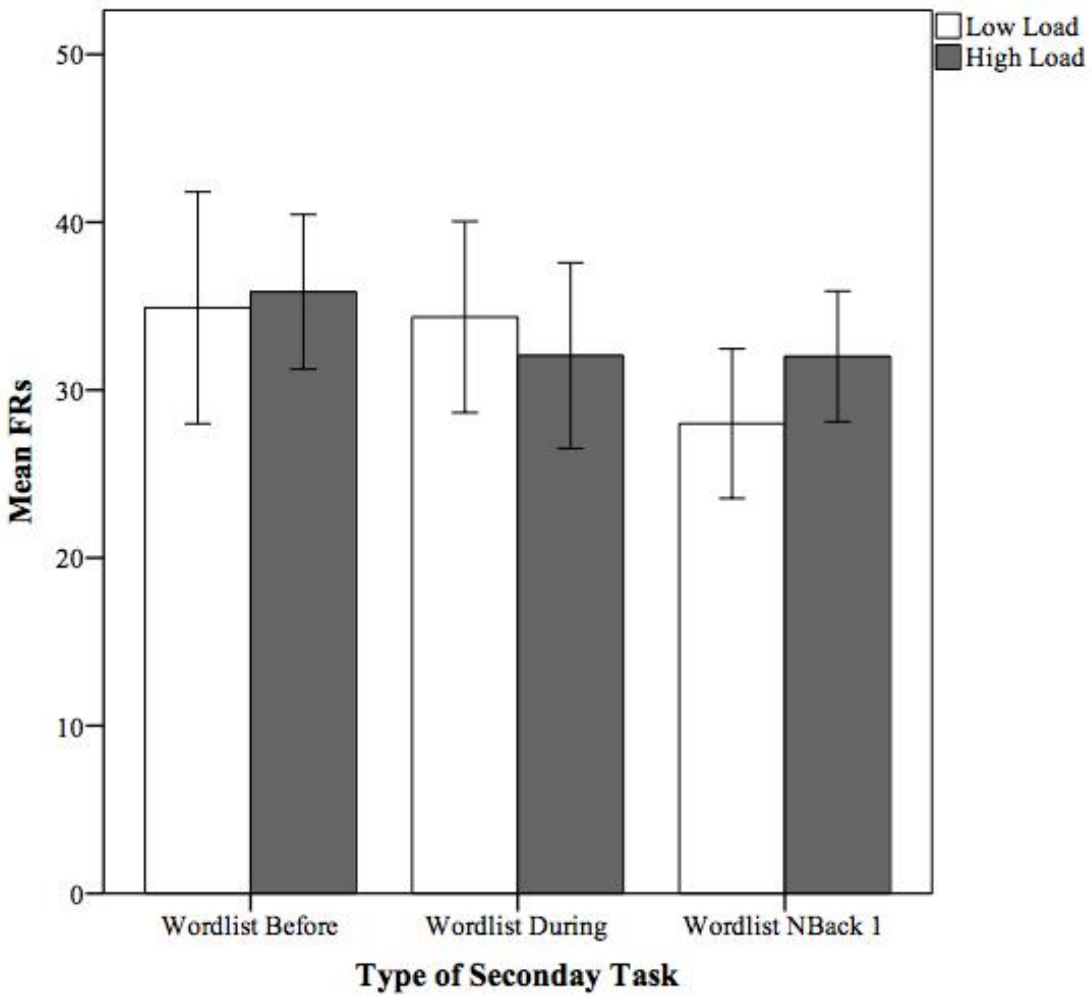


Figure 5, *Mean False Responses (FRs) to non-hazardous events in the primary task between high and low cognitive load conditions across the three different secondary tasks including error bars indicating 1 S.E.*

Discussion

The aim of this experimental chapter was to determine whether individual component processes involved in engaging in a conversation have different effects on hazard perception performance. A series of three experiments isolated processes of (1) working memory; (2) combined processing of verbal information and working memory; (3) combined processes of computing and producing verbal information along with working memory. In each case, their effect on hazard perception performance was compared to a low cognitive load condition in which participants were required to answer a simple question. Experiment 1 isolated processes of working memory by presenting a standard working memory task prior to the beginning of each hazard perception clip.

Experiment 2 built upon this by including the process of computing verbal information to the working memory element. Finally, Experiment 3 expanded on this by including the element of speech production with processes of working memory and verbal comprehension. Regardless of which secondary task was being performed, RTs in the primary hazard perception task were significantly increased as a consequence. Analyses across all three experiments indicated that there was no difference in the cost to RTs, FRs or Hits associated with any of the three secondary tasks.

The fact that each of the three secondary tasks had the same effect on hazard perception performance suggests that in terms of the detriments caused to hazard perception performance working memory impairments have the largest effect. Including both elements of simultaneous language comprehension and production does not significantly affect hazard perception performance over and above that of the impairments caused by increases in working memory.

Previous research has found little to no difference in terms of the distraction elicited between hands-free and hand held devices (Patten, Kircher, Östlund & Nilsson, 2004, Treffner & Barrett, 2004). Furthermore, driving performance is impaired both during (Strayer & Johnston, 2001) and for a period after the actual conversation (Redelmeier & Tibshirani, 1997; Haigney & Taylor, 1998). Taken together previous research as well as this current study suggested that the cognitive task demand associated with holding a conversation might be the root cause of the observed performance detriments, rather than processes of language processing and production. As discussed in chapter 1 of this thesis, although conversing on a mobile telephone requires a large variety of different cognitive sub-processes, we argue that working memory plays a vital role in retaining important information in order to choose an appropriate response. Memory for conversations has been demonstrated to be stored in a general gist-type fashion wherein context and semantics play a role in memorizing the message of a particular communication (Stafford, Burggraf & Sharkey, 1987). Memory for wordlists is different from this, as it requires subjects to remember the exact words used rather than a general gist. However it is argued that, as working memory is required for both memory for wordlists and memory for conversations, the secondary tasks chosen in this current series of experiments not only isolate processes of working memory, language processing and production but also afford a more meaningful quantification of secondary memory task performance in comparison to traditional conversation tasks. Previous research has attempted to isolate individual components of the larger conversation task such as listening to someone speak (Strayer & Johnston, 2001), contemplating the content of a previous conversation (Savage, Potter & Tatler, 2013) as well as actively producing language (Alm & Nilsson, 1994). Results from this current series of experiments demonstrate that processes of listening to and producing language do not lead to a significant decrease in hazard perception performance over and above the impairments caused by increases in working memory.

The similarity in performance across all three secondary tasks is most likely due to the fact that all three tasks involved higher-level executive functions such as working memory, which are also required to maintain primary task performance. Typically dual task models predict that simultaneously performing a secondary task has a detrimental effect on driving performance if both tasks draw upon similar resources. However the allocation of resources between both tasks can be mediated flexibly in order to free up capacities for the task that requires the most attention (Wickens, 2002; Robert & Hockey, 1997). Models of executive control such as

Norman & Shallice's (1986) postulate separate control mechanisms: one low-level automatic contention scheduling system and one higher order supervisory attentional system which involves top-down control of behaviour. Schemas, another component of these models, are thought to consist of patterns of behaviours that achieve a given task. When the primary driving task is easy, schema are thought to be capable of coordinating vehicle control. During these routine-driving situations, if more than one schema becomes activated the contention scheduling system decides which one receives priority. In the event that a situation requires a non-habitual or novel response, the supervisory attentional system is thought to be able to modulate attention resources. In terms of dual task performance these models predict that conversing on a mobile phone whilst driving will not affect task performance as long as the primary task is easy enough to be handled by automatic schema. This frees up higher-level executive functions such as working memory in order to cope with the increased demands associated with conversing on a mobile phone. When the primary driving task becomes difficult however, supervisory control processes become necessary for the maintenance of primary task performance as well as mobile phone use. Thus, driving performance deteriorates when both tasks overload the resources of the supervisory control system. Real life driving and simulated driving research have shown that driver's were able to compensate for increases in secondary cognitive task demand by reducing the difficulty of the primary task, for instance by driving slower **(**Patten et al., 2004**)**.

This type of compensatory behaviour is described by Hockey's (1997) compensatory control model that argues that subjects attempt to maintain primary task performance by means of different strategies. Such strategies include the freeing up of resources by making conscious concessions in the primary task by driving slower or focussing on more basic goals such maintaining vehicle heading. As the driving hazard perception task is not a self-paced activity, we argue that it is a valuable tool with which to assess the affects of secondary cognitive task demand on the perceptual processes involved in driving situations.

As working memory is crucial to good hazard perception performance and there are differences in working memory capacities between individuals (e.g., Lezak, 2004) one might expect differences in the effect of secondary cognitive task demand to relate to individual differences in working memory capacity. Therefore we were interested in determining whether subjects' initial digit span was correlated with measures of hazard perception performance. Contrary to expectations, digit span was only correlated with RTs and inversely correlated with FRs on high load trials in which the wordlist had been presented prior to the start of each hazard perception clip ('Wordlist Before'). However this relationship was not present in either 'Wordlist During' or 'Wordlist n-back' trials. Correlations implied that individuals with higher digit span performance were associated with longer RTs and fewer FRs. This relationship indicated that in terms of FRs, people with higher digit spans might have been more efficient at computing dual tasks. This interpretation seems to be contradicted by a positive correlation of digit span and RTs. However if we consider the differences in RTs and FRs between high and low cognitive load condition, one possible interpretation of the fact that we found a significant increase in RTs but did not find any increases in FRs or decreases in Hits may be that the sharing of resources across different tasks affects primarily the speed at which decision processes are being made rather than the effectiveness of these processes themselves. It could for instance be argued that the increase in workload results in a corresponding increase in concentration (Crundall et al., 2005), which leads to participants avoiding certain behaviours such as responding to non-hazardous events or not responding to hazardous events but still incurring a cost to RTs due to the demands of the secondary task. Therefore this pattern of correlations may indicate that when cognitive task demand is high, people with higher digit spans are better at processing hazards and non –hazards but take more time to do so. However, it should be noted that these correlations are based on a sample of 20 participants who performed 10 trials each in the high cognitive task demand condition and therefore these correlations are susceptible to individual differences and should be interpreted with caution.

Correlations between participants’ secondary and primary task performance indicated no relationship between secondary memory and hazard perception performance on either wordlist before or wordlist during tasks. If one task would have been prioritized over another, one might have expected a significant correlation between secondary and primary task performance. A positive correlation between memory performance and RTs for instance may have suggested that participants were prioritizing the secondary over the primary task: more words remembered being associated with longer RTs. However a negative correlation between RTs and memory performance might have indicated a prioritisation of the primary task: fewer words remembered being associated with shorter RTs. However in terms of the prioritization of primary and secondary tasks, this current study found no clear relationship between primary and secondary task performance. This may be for several reasons. For instance, it might be argued that all three secondary tasks occupied sufficient working memory resources that schematic processing of the primary task was not possible. As subjects were not able to reduce primary hazard perception task difficulty (i.e. by slowing down presentation speed of the videos) they were not able to free-up enough resources to compute either task at an optimal level. This may have resulted in a general decrease in performance on both primary and secondary tasks without a clear trade-off for one over the other. Furthermore results indicated no correlations between digit span and memory performance on any of the three secondary tasks. Most dual task models (Wickens, 2002; Hockey, 1997, Norman & Shallice, 1986) postulate a flexible mediation of attention between primary and secondary task. As the hazard perception task does not allow for regulation of primary task difficulty, it may be feasible to assume that the hazard perception task requires a considerable proportion of resources, which results in a general decrease in recall performance regardless of an individuals prior digit span. Taken together these results may imply that when drivers are unable to regulate primary task difficulty, secondary cognitive task demand manipulations result in a decrease in performance on both tasks rather than a prioritization of one task over the other.

It could, however, be argued that hazard perception clips do not always require the same intensity of processing at any given moment of the video. This means to say that there are comparatively easy periods of a clip in which little new information is presented, especially when no potential hazards were present and more difficult periods of the clip when many potential hazards need to be monitored. Although hazard perception clips were balanced in terms of their visual information across videos, it could be reasoned that participants' processing of the primary hazard perception task was altered when a potential hazard was present on screen in comparison to when no potential hazards were present. Therefore the fact that we currently found no significant correlation between secondary memory and primary hazard perception task performance does not necessarily mean that compensatory behaviour did not occur. It is more likely that the prioritisation of primary and secondary task processing is much more dynamic, changing moment to moment with new perceptual input (Norman & Shallice, 1986). As correlations between secondary memory and primary hazard perception performance are based on the full one minute periods of the hazard perception clip these analyses would only have revealed an overall prioritisation of the primary or the secondary task but no flexible mediation of resources within each trial.

Therefore one aim of the final experimental chapter of this thesis will be to distil periods within the primary task in which potential hazards are present and examine whether the susceptibility of these periods to increases in secondary task demand are different from comparatively easy periods within each clip when no potential hazards are present. Previous literature suggests that primary driving task performance is only affected by secondary task demand manipulations when the primary task is easy (Alm & Nillson, 1994), therefore it is predicted that increases in cognitive load will have less of an effect on physiological measures such as eye movements when the hazard is present compared to when it is absent.

Chapter V

The effects of secondary cognitive task demand on behavioural, oculomotor and electrophysiological measures within a hazard perception paradigm.

Introduction

The aim of the previous chapter of this thesis was to isolate the individual component processes of mobile call conversation and to examine their effect on hazard perception performance. One question that was raised was the susceptibility of hazard perception performance to increases in secondary cognitive task demand depending on the current content of the hazard perception task. Previous research has indicated that when the primary driving task becomes difficult the intrusion of secondary cognitive task demand becomes attenuated (Alm & Nillson, 1994**)**. One advantage of the hazard perception task is that it is not a self-paced activity, this means to say that subjects are unable to reduce the presentation speed of the videos thus freeing up resources to compute both dual tasks. However it could be argued that the content of the primary task is variable within each clip as there are periods in which a potential hazard is present and periods where clearly no potential hazards are present. As the primary hazard perception task does not allow for a reduction in driving speed, we were interested in determining whether compensation for increases in secondary cognitive task demand are reflected by more subtle changes in behaviour within the primary task. Therefore in addition to examining overall differences between high and low load conditions, the aim of this current experiment was to determine whether previously identified oculomotor markers of cognitive distraction were affected differently by cognitive load when a potential hazard was on-screen compared to when no potential hazards were present.

Previous research by Savage, Potter & Tatler (2013) indicated that cognitive preoccupation had detrimental effects on behavioural, oculomotor and electrophysiological metrics within a hazard perception task. The aim of Savage et al.'s (2013) study was to examine differences in overall (tonic) changes resulting from increases in secondary cognitive task demand; that is, whether distraction resulted in globally different viewing behaviour and cortical activity across the entire 1-minute hazard perception clip. The two main aims of the current experiment were 1) to replicate previous analyses in terms of global differences in behavioural, oculomotor and electrophysiological metrics; and 2) to examine differences in event related changes within these measures. This means to say that 1) behavioural and oculomotor measures were analysed between high and low cognitive load conditions; and 2) the susceptibility of these measures to increases in secondary cognitive task demand was examined across three different periods within each clip (before, during and after the hazard was on screen). As the hazard perception task does not allow subjects to directly influence the presentation speed of the videos, it was predicted that compensatory behaviour would be reflected in more subtle changes in viewing behaviour and electrophysiology. Furthermore as models of executive control (e.g., Norman & Shallice, 1986) predict that the intrusion of secondary tasks can become attenuated depending of the content of the primary task, differences in the susceptibility of oculomotor metrics to increases in cognitive task demand may indicate which portion of the hazard perception task was most demanding for participants (before, during or after the hazard onset).

In order to better control the hazard perception videos in terms of their perceptual load, the original 1-minute hazard perception clips were shortened to 30 seconds and contained only one clearly identifiable hazard period.

As in Chapter 4, primary hazard perception task performance was assessed by means of Reaction Times (RTs) and hits (correct detection of the hazard), as well as False Responses (FRs) to non-hazardous stimuli. As with previous experiments of this thesis, oculomotor measures consisted of: fixation durations, number of fixations, saccade peak velocities, saccade durations, saccade amplitudes, blink rates and durations as well as x and y fixation position variance.

Results across a wide variety of driving tasks have shown that the introduction of a secondary cognitive task resulted in a significant reduction of the spread of fixations within the primary task leading to more time being spent fixating on the centre of the road (Recarte & Nunes; 2000, Harbluk, Noy & Eizenman 2002; Victor, Harbluk & Engström, 2005; Reimer, 2009).

Previously, Harbluk, Noy & Eizenman (2002) manipulated the complexity of the secondary mobile telephone conversation, which, along with an increase in the percentage of time spent fixating on the centre of the road, resulted in a concurrent decrease of saccade numbers.

As discussed in Chapter 1, different elements of blinks have been thought to be indicators of both fatigue and mental workload and have been shown to increase as a function of time on task. Therefore it has been argued that blink rates may be a good indicator of mental fatigue and cognitive workload (Fukuda, Stern, Brown & Russo, 2005; Stern, Boyer & Schroeder, 1994). Furthermore previous research has demonstrated that blink durations decreased as a function of primary visual task demand (Ahlstrom & Friedman-Berg, 2006, Benedetto et al., 2011).

In previous experiments of the current thesis, saccade peak velocities were altered to some extent by the introduction of a secondary cognitive task. In a previous hazard perception task, high secondary cognitive task demand resulted in a significant increase in saccade peak velocities (Savage et al., 2013). Previous research has found that peak velocities were also affected by mental activation (App & Debus, 1998), alertness (Thomas & Russo, 2007), and mental workload (Di Stasi et al., 2010) as well as drug-induced sedation, sleep deprivation and fatigue (Grace et al., 2010; Zils et al., 2005, Schmidt et al., 1979).

Saccades vary in amplitude, duration and peak velocity (Dodge & Cline, 1901, Dodge, 1917). The relationship between these individual parameters has come to be known as the ‘main sequence’ - a function that describes a systematic increase of saccade durations and peak velocities with increases in amplitudes (Bahill et al., 1975). In order to determine whether changes in saccade peak velocities were due to changes in secondary cognitive load and not merely a by-product of changes to saccade amplitudes or durations, these two measures were included in our analyses. Fixation durations are often considered to reflect processing time, especially in reading where words that are more difficult are fixated upon for longer (Rayner, 1998). Previous work by Velichkovsky et al. (2002) has shown that the first fixation upon a hazard was typically much longer in duration than those preceding the hazard. The question remains whether fixation durations are only sensitive to changes in visual task demand or whether secondary cognitive task demand also influences the durations of fixations. We argue that the analyses of fixation durations for the periods before, during and after the hazard window may indicate which portion of the hazard perception task was most affected by cognitive load.

Therefore this current study considered the effects of secondary cognitive load on average spread of fixations along x- and y-axes, the total number of fixations, blink rates and durations as well as saccade peak velocities. As events in the primary task (such as the appearance of the hazard) most likely interfere with processes of visual processing we were especially interested in determining not only the effect of hazard presence but also any possible interactions with cognitive load. An interaction between time window and cognitive load would indicate that secondary task demand has a different effect across two different windows.

Cortical activity was analysed using two approaches. Previous driving simulator research has shown that EEG metrics such as frontal theta frequency (4-8 Hz) output may be a good indicator of early distraction and driver inattention (Lin et al., 2011). Other frequency metrics that have been demonstrated to be related to cognitive distraction were alpha (8-14 Hz) and beta (14-35 Hz) bands. Increases in cognitive task demand resulted in a significant decrease or desynchronization of alpha band activity (Klimesch et al., 1999; Wolfgang, 1999) and a significant increase or synchronization of theta activity (Tulving, Kapur, Craik, Moscovitch & Houle, 1994). To begin with we were interested in replicating Savage's et al. (2013) EEG frequency analyses of activity during the entire hazard perception videos, which have demonstrated increased frontal theta when participants were preoccupied by solving puzzles. In addition to examining differences in theta band frequency activity, we were interested in determining whether there were any differences in alpha and beta band power between high and low load conditions.

The second approach to quantifying cortical activation involved the analyses of specific sections of the EEG to determine if 1) there were differences in event related theta, beta and alpha frequency band output and 2) differences in event-related potentials around fixations, as well as behavioural responses, between high and low cognitive task demand conditions.

Frequency band analyses have not only been used to determine overall differences between high and low cognitive load conditions. Research by Lin et al. (2011) indicated that dual tasks elicit more event-related EEG activity in the theta band around the time of the hazard onset. Therefore the aim of this current experiment was to determine whether frequency activity in response to the hazard onset differed between high and low cognitive load conditions.

In Savage et al.'s (2013) hazard perception study, the authors analysed differences in frontal and occipital theta frequency output for the entire duration of each one-minute hazard perception clip. Results demonstrated significantly more frontal and less occipital theta frequency band output in the high compared to the low cognitive task demand condition. One interpretation that was offered by the authors in terms of the decrease in occipital theta was a decrease in visual processing, most likely associated with the observed reduction in spread of fixations. To test this hypothesis the current study examined differences in fixation related ERPs (fERPs) between high and low cognitive task demand conditions.

One question that has been raised in the previous chapter of this thesis was how primary hazard perception performance was being maintained during dual task situations. Results from Chapter 4 can be used to suggest that the sharing of resources across different tasks affects primarily the speed at which decision processes are being made rather than the effectiveness of these processes themselves. This was demonstrated by an increase in RTs but not FRs. One way to examine the effects of cognitive load on the decision-making processes involved in hazard perception was to compare average event-related potentials immediately preceding and subsequent to participants' correct or incorrect responses.

In order to determine whether the secondary cognitive task interferes with processes of preparation and attention, contingent negative variations (CNVs) were compared between high and low load conditions. Stimulus preceding negativity (SPN) or historically CNVs, are slow, surface-negative electrical brain waves that were originally described as dependent on the association (or contingency) of two successive stimuli (Walter et al., 1964). Paradigms for generating CNVs involve a warning stimulus and an imperative stimulus that requires a motor response. The CNV is observed between warning and imperative stimuli as a negative shift in the EEG baseline averaging approximately 20 microvolts. Previous research has indicated that the CNV response may be associated with processes of expectancy (Walter, 1965, Walter et al., 1964), intention (Low, Borda, Frost & Kellaway, 1966), motivation (Irwin, Knott McAdam & Rebert, 1966) and attention (McCallum, 1969, Tecce & Sheff, 1969). Furthermore the amplitudes of CNVs were reduced by exogenous distractions such as conversations (McCallum & Walter, 1968, Walter et al., 1967) and listening to classical music (McCallum & Walter, 1968) as well as endogenous distractors such as a full bladder (McCallum, 1967) or daydreaming (Rousseau, Bostem & Dongier, 1968). In addition to indicating sustained distractions (over a large number of trials), reductions of CNV amplitudes have been demonstrated in more discrete (phasic) distraction conditions within individual trials (Tecce & Scheff, 1969). Research by van Boxtel and colleagues highlighted that an important factor in the magnitude of the CNV was the relationship to preparation for the processing of upcoming stimuli and this led to the more general description of Stimulus Preceding Negativity (SPN – e.g. van Boxtel et al., 2004). Thus analysing SPN amplitudes between high and low cognitive load conditions may indicate 1) tonic differences in attention and preparatory processes prior to the onset of each hazard perception clip; and 2) phasic differences in the processes of attention and preparation prior to correct and incorrect responses.

Method

Design

In this within-subjects experimental design the independent variable was secondary cognitive task demand, which was either high or low. Cognitive load was manipulated by the type of audio clip presented to participants prior to the beginning of the trial.

Cognitive load was considered to be high following a wordlist that the participant was required to rehearse during each hazard perception clip and recall at the end of it. Participants' performance was compared to control trials following an easy question (e.g., "*What is the capital city of England*"), which participants were required to answer at the end of each trial (low cognitive load). The dependent variables were grouped into three major categories: (1) behavioural, (2) oculomotor, and (3) electrophysiological. Behavioural independent variables consisted of participants' RTs to hazardous events, False Responses (FRs) to non-hazardous events and Missing Responses (MRs) to hazardous events. In our analyses we only analysed RTs to the hazardous events. Dependent variables relating to oculomotor metrics consisted of fixation durations, saccade amplitudes, average saccade peak velocities, changes in saccadic peak velocities over time, the spread of horizontal and vertical fixation positions, blink frequencies and blink durations. Dependent variables relating to electrophysiological metrics consisted of overall average mid-theta (4 - 7 Hz Band), alpha (8 -15 Hz Band) and low beta (16 – 24 Hz Band) frequency power outputs, average high theta (6 – 10 Hz Bands), high alpha (12 – 15 Hz Band) and low beta (16 – 24 Hz Band) frequency outputs for the window 1000 ms prior to and 5000 ms after the hazard onset, average stimulus preceding negativity (SPN) in the window 1500 ms prior to and 1500 ms after the beginning of each hazard perception clip, average activity in the window 500 ms prior to and 1000 ms after each correct response and false response and average SPN in the window 1000 ms prior to and 1000 ms after each correct and false response. We were also interested in average activity in the window 150 ms prior to and 600 ms after the onset of each fixation. Time windows were chosen following an exploratory analysis of the average difference size between the two conditions across time, in BrainVision.

Participants

17 Participants (7 male and 10 female) were recruited in and around the University of Dundee by means of the Universities Research Participation System ‘‘*SONA*’’. All testing was carried out in the Research Wing of the School of Psychology at the University of Dundee. Participation typically lasted no longer than 2 hours and participants were compensated with either course-credit or chocolate. Participants’ ages ranged between 18 and 28. To ensure all participants were familiar with the hazard perception portion of the test, all subjects were required to be in possession of a DVLA approved driver’s license and must have been driving for a minimum of 1 year.

Materials

Participants sat at a table with their heads supported by a chinrest 62.5 cm away from a 20” CRT-Monitor on which the visual stimuli were displayed. Subjects were instructed to indicate their responses using *SR-Research* button boxes. Experiment Builder software by *SR-Research* was used to program the presentation of the audio and visual stimuli.

Participants’ eye movements were recorded using an EyeLink1000 eye-tracker sampling at 1000 Hz and cortical activity was recorded using a 40 channel, BioSemi active electrode system sampling at 2048 Hz, which was connected to a dedicated recording computer utilising BioSemi - Activision software.

For this study we used a total of 32 DVLA approved hazard perception clips, which were provided courtesy of Focus Multimedia Ltd. and Imagitech Ltd. We made use of sixteen 10-item wordlists (compounded from the 15-item wordlist used in Experiment III – see appendix for materials) and sixteen easy to solve questions to manipulate cognitive load. These wordlists and questions were presented via a set of Logitech loudspeakers at a comfortable but constant volume.

Procedure

Participants were instructed to fixate on a central fixation point prior to beginning of each trial. Depending on the condition, participants were presented with an easy question (low cognitive load condition – e.g. ''*What is the capital City of Scotland?*'') or a 10-item wordlist (created from 15-item wordlists from the previous experiment - high cognitive load condition) directly before the start of the hazard perception clip. Words within the wordlist were presented at a frequency of 1 every 3 seconds resulting in a total audio duration of 30 seconds and each hazard perception clip was of a fixed length of 30 seconds. In both conditions participants were instructed to indicate the onset of hazards in the clip by pressing a button on a response-box. At the end of each trial, depending on the condition, participants were asked to state the answer to the previously presented question (low load) or recall as many words as possible from the previously presented wordlist (high load).

Participants completed 1 practice trial from each condition prior to the start of testing to familiarize them with the procedure. Participants then completed 15 trials in each condition. The presentation order of trials was randomised and the pairing of hazard perception clip and type of audio clip was counterbalanced across participants. EEG and eye movement data were recorded for the full duration of each trial

EEG recording

Stimuli were presented using SR-Research Experiment-Builder software with event codes simultaneously sent to the EEG recording system via the TTL parallel output port. Event codes were used to define each clip as well as its appropriate condition in order to guide later analysis. In order to be able to analyse fixation related potentials as well as EEG activity prior to correct and incorrect responses, the timings of fixations, saccades and behavioural events were extracted from the raw data and merged with the stimulus events by means of custom-made MatLab routines (as described in Chapter 2 of this thesis). Recordings were carried out using a BioSemi CHA-01 with a digital sampling rate of 2048 Hz. We used 32 electrodes fitted to an elastic cap. Electrodes were placed according to the 10–20 system at scalp sites of Fp1, Fp2, AF3, AF4, F7, F8, F3, F4, Fz, FC1, FC2, FC5, FC6, T7, T8, C3, C4, Cz, CP1, CP2, CP5, CP6, P3, P4, Pz, P7, P8, PO3, PO4, O1, O2, Oz. Additionally, electrodes were positioned above and below the right eye (EXG1 & EXG2) to monitor the timings of vertical eye movements (VEOGs), at the outer canthi of both eyes (EXG3 & EXG4) for horizontal eye movements for later artifact removal, and on the left and right mastoids (EXG5 & EXG6) and nose (EXG) to provide alternative reference sites. Electrode sites were prepared with alcohol to reduce scalp impedances. Sigma conductivity gel was applied to each cap electrode fitting point. After pre-processing, the data were ultimately analysed using BrainVision Analyser software.

<u>*EEG data processing*</u>

In the data pre-processing stage the EEG recordings were down-sampled to the same rate as the Eye Tracker (1000 Hz) using BDF Decimator82. Recordings were then re-referenced to the linked nose reference site using PolyRex version 1.2 (Kayser & Tenke, 2003). Stimulus event codes were used to first segment out all valid trials from the continuous EEG data. At this point the data were Baseline Corrected (BC) based on the window1500 ms prior up to the start of each hazard perception clip. The data were then processed for further analyses with a Butterworth Zero Phase Filter with low cut-off frequency of 45 Hz and a high cut-off frequency of 0.53 Hz with a time constant of 0.3 and a 48dB/oct slope. An Ocular Correction Independent Component Analysis (OC ICA) was then performed on the whole data using EXG1 re-referenced to EXG2 to identify blink activity and EXG3 re-referenced to EXG4 to identify horizontal eye movement activity. Stimulus event codes were then used to segment the data into high and low load conditions for further analyses.

Combining EEG and Eye Tracking

The timings of saccades, fixations, blinks and behavioural responses were extracted from the raw data and merged with the corresponding EEG recordings. This methodology was developed at the start of the present thesis and is described in Chapter 2.

Stimulus event codes included the start of the audio clip, the end of the audio clip (along with condition identifiers) as well as the start and end of each hazard perception video. Behavioural event codes included fixations, saccades, blinks and motor responses.

EEG analysis

Overall Frequency differences between conditions

Fast Fourier Transformation was performed on the entire 30 second epoch of each hazard perception trial using a periodic 10% Hamming Window and a resolution of 0.03125 Hz. We then averaged the results for each condition and compared overall power in mid-theta (4 - 7 Hz Band), alpha (8 -15 Hz Band) and low-beta (16 – 24 Hz Band) frequency outputs. Overall power for these frequency ranges for each region was calculated by measuring the area under the curve of on-going fluctuations in theta, alpha and beta band power for each epoch in both high and low cognitive load conditions

Frequency differences following Hazard Onset

Fast Fourier Transformation was performed on the epoch 1000 ms prior to and 5000 ms after the hazard onset using a periodic 10% Hamming Window and a resolution of 0.125 Hz. We then averaged the results for each condition and compared overall power in high theta (6 – 10 Hz Bands), high alpha (12 – 15 Hz Band) and low beta (16 – 24 Hz Band) frequency outputs. Overall power for these frequency ranges for each region was calculated by measuring the area under the curve of on-going fluctuations in theta, alpha and beta band power for each epoch in both high and low cognitive load conditions

Differences in SPNs directly prior to the beginning of hazard perception trials

Stimulus event codes were used to segment a window 1500 ms prior to and 3000 ms after the beginning of hazard perception trials. These segments were then averaged in order to analyse differences between SPN prior to the beginning of both high and low load trials.

Differences in SPNs directly prior to correct and incorrect responses

Stimulus event codes and behavioural event codes were used to segment a window 1000 ms prior to and 2000 ms after correct and incorrect responses. Segments were then averaged in order to analyse differences between SPNs prior to incorrect and correct responses.

Differences in activity after correct and incorrect responses

In addition to analysing differences in SPNs prior to correct and incorrect button press responses, we were interested in determining average differences after both correct and incorrect responses between high and low cognitive load conditions. Stimulus event codes and behavioural event codes were used to segment windows 500 ms prior to and 1000 ms after each correct and incorrect response. Segments were then averaged in order to analyse differences in overall activity following correct and incorrect responses between high and low cognitive load conditions.

Differences in fixation event-related potentials (fERPs)

Fixation event codes were used to segment windows 150 ms prior and 600 ms after the onset of each fixation. These segments were first baseline corrected (BC) on the epoch 150 ms prior to fixation onset and then averaged across conditions in order to determine differences in overall activity after each fixation between high and low cognitive load conditions.

Eye movement recording

Eye movements were recorded using an SR Research EyeLink1000 eye-tracker, sampling at 1000 Hz. Each participant completed three brief eye dominance tests prior to the start of testing so that the experimenter was able to track the subject's dominant eye. A 9-point calibration procedure was used to calibrate the tracker and repeated to validate tracker accuracy. If the validation procedure showed an average error in excess of 0.5° or a maximum error in excess of 1°, the calibration procedure was repeated. Saccades were identified using the standard SR Research algorithm, which detects saccades when eye position deviates by more than 0.1°, with a minimum velocity of 30 deg s^{-1} and a minimum acceleration of 8000 deg s^{-1}, maintained for at least 4 ms. Data were exported to custom-made MatLab routines for subsequent analysis of saccade, fixation and blink events.

Statistical analysis

Data were analysed using Linear Mixed Models (LMMs) using the *lme4* package (version, 1.1-7; Bates et al., 2014) in the *"R"* statistical programming environment (R

Development Core Team, 2007). LMMs are particularly well suited to datasets such as those collected in this study for several reasons: 1) they are able to deal with uneven distributions of data between conditions in the design; 2) they can combine continuous and categorical factors within the same model; and 3) they can measure variance across subjects and items simultaneously (Kliegl et al 2012). In constructing models, time window (before, during and after hazard onset) and cognitive load (high vs. low) were entered as fixed effects whereas subjects and items (hazard perception movie) were entered as random effects in all models. For the random effects structure we attempted to include random slopes and intercepts for all fixed effects and their interactions in order to produce a maximal random effects structure (Barr et al., 2013). However, maximal structure models often fail to converge. When these models did not converge, we first removed the computation of correlation parameters within the random effects structures. If further simplifications were required for model convergence, we began by simplifying the item term, first, by removing the slopes for the interaction between time window and cognitive load. Following this, the random slope for time window was removed from the item term before removing the slope for cognitive load if necessary (leaving an intercept-only item term in the random effects structure). Throughout simplification of the item term the full structure for the subject term was retained (minus correlation parameters). If models still did not converge once the item term was simplified, the same stepwise simplification procedure was followed for the subject term. In the sections that follow the results are reported for the most complex random effects structure for which the LMM converged. In order to calculate *p*-values LMMs were created which were identical to the original models with the exception of the factor being removed from the fixed effect term for which the p-value was to be determined. These new models were compared to the original model using an analysis of variance (ANOVA). As model comparisons were not possible to determine *p*-values for factors with more than two levels, significance values for differences between time windows were interpreted by means of the *t*-statistic. Given the large amount of observations for each participant the *t*-statistic (i.e. the average effect size / standard error) effectively corresponds to the *z*-statistic (Kliegl et al., 2013). Effects larger than twice their standard errors were interpreted as significant beyond the 5% level (*t*-value => 2).

Analyses were carried out on two levels. At the first level, overall differences between high and low load conditions were examined for all dependent variables. At a second level, the hazard perception clips were segmented into time windows. These time windows were defined as being 1) before the onset of the hazard 2) during the period in which the hazard was on screen; and 3) after the hazard had disappeared from the screen. The second level of analysis was aimed at examining the susceptibility of our dependent variables to increases in cognitive load across these three time windows.

Neurophysiological Measures

Participants' grand averages (GAs) for each frequency band were calculated by measuring the area under the curve for each pre-defined frequency range within a specified time window. Similarly, GAs for ERP and SPNs measures were generated by calculating the area under the curve of on-going fluctuation within the specified time windows. A text file containing participants GAs at each of the 32 electrode sites for high and low cognitive load conditions was exported from BrainVision. In order to explore at which electrode sites significant differences between high and low load could be identified, GAs were analysed in SPSS using paired-samples t-tests.

Results

Behavioural Measures

To examine overall differences between conditions irrespective of time windows, the construction of LMMs was carried out as described above without including time window in the fixed effect term. Measured from the appearance of the hazard on screen we found no significant effect of cognitive load on RTs (b= .01; SE= .03; t= -.32; p = .74) or FRs (b= -.19; SE= .11; t= -1.82; p= .08). Analyses of MRs were not carried out, as there were no recorded cases. Average RTs, FRs and MRs for both high and low cognitive task demand conditions can be seen in Table 1.

Table 1*, Average reaction times (RTs) in milliseconds, false responses (FRs) and missing responses (MRs) per clip between both high and low cognitive load conditions along with standard deviations (in parentheses)*

Measure	**High Load**	**Low Load**
RTs [*ms*]	2702.98 (*1913.42*)	2667.99 (*1635.9*)
FRs [*per clip*]	1.32 (*1.51*)	1.4 (*1.65*)
MRs [*per clip*]	N.A.	N.A.

Oculomotor Measures

Analyses of oculomotor measures were carried out on two levels: First, overall main effect of cognitive task demand (high or low) on number of fixations, saccade peak velocities, saccade durations, saccade amplitudes, blink rates and durations as well as x and y fixation position variance, were examined for the entire 30 second duration of the hazard perception clip. As with behavioural measures a separate LMM was constructed for each variable, resulting in models each containing a fixed effect of cognitive load and two random factors for item and subject.

Overall differences between high and low cognitive load conditions

There was no significant main effect of cognitive load on the number of fixations (*b*= -2.66; *SE*= 1.99; *t*= -1.34; *p*= .18), saccade amplitudes (*b*= -.03; *SE*= .06; *t*= -.45; *p*= .64) or saccade durations (*b*= .017; *SE*= .009; *t*= 1.91; *p*= .06). However we found longer first saccade latencies (*b*= .06; *SE*= .02; *t*= 2.63, *p*= .013) and faster saccade peak velocities (*b*= .01; *SE*= .006; *t*= 1.99; *p*= 0.049) in the high compared to the low cognitive task demand condition. Horizontal (*b*= -807.4; *SE*= 539.4; *t*= -1.5; *p*= .14), and vertical (*b*= 392.8; *SE*= 300.3; t= 1.31; *p*= .19) position variance were not affected by load. However averages indicated that horizontal position variance was smaller in the high compared to the low cognitive load condition. Blink rates were significantly increased in the high compared to the low cognitive task demand condition (*b*= 2.86; *SE*= .58; *t*= 4.95; *p*< .001) whereas blink durations were unchanged (*b*= .05; *SE*= .04; *t*= 1.41; *p*= .15). A summary of average oculomotor measures between high and low load conditions can be seen in Table 2.

Table 2, *Average Number of Fixations (NFix) per clip, Fixation Durations (Fix. Durs) in milliseconds, Saccade Amplitudes (Sacc. Amps) in degrees, Saccade Durations (Sacc. Durs) in milliseconds, Saccade Peak Velocities (Sacc. PVs) in degrees per second, First Saccade Latencies (First Sacc.Lat) in milliseconds, horizontal and vertical spread of fixations (position variance; in pixels), Blink Numbers (N.Blinks) per clip and Blink Durations (Blink Durs) in milliseconds along with standard deviations (in parentheses).*

Measure	**High Load**	**Low Load**
Nfix.	66.28 (*14.1*)	68.86 (*12.61*)
Fix. Durs. [*ms*]	366.46 (*231.46*)	366.027 (*222.85*)
Sacc. Amps [*deg.*]	2.6 (*2.14*)	2.6 (*2.18*)
Sacc. Durs [*ms*]	31.39 (*31.85*)	29.27 (*20.69*)
Sacc. PVs [*deg/sec*][1]	202.02 (*120.16*)	195.63 (*115.14*)
First Sacc.Lat [*ms*][1]	344.33 (*215.26*)	288.5412 (*152.16*)
X-Spread [*pixels*]	12346.66 (*7407.22*)	13149.47 (*7914.36*)
Y-Spread [*pixels*]	2242.221 (*2935.42*)	1851.529 (*2593.03*)
N.Blinks [*per clip*][1]	10.03 (*6.91*)	7.17 (*5.32*)
Blink Durs [*ms*]	298 (*942.15*)	244.9 (*533.13*)

1 Denotes a significant difference between high and low cognitive load conditions

Analyses by Time Window

In the second level of analyses, stimulus event codes signifying the first frame in which the hazard appeared and disappeared from the visual scene were used to segment hazard perception clips into three periods: before hazard onset, during hazard appearance and after hazard disappearance. Separate LMMs were constructed for each variable as described above with time window and cognitive load as fixed effects as well as item and subject as random effects. Planned contrasts were set up in such a way as to compare the periods before and after with the period during which the hazard was on screen. Interactions between cognitive load and time window were carried out by means of model comparisons. To this effect the last converging model for each measure was constructed without the interaction between the two fixed effects. This model was then compared to the original LMM by means of an ANOVA.

Measures that were included in our analyses between time windows were fixation durations, variance of spread along the x-axis, number of fixations, saccade peak velocities, saccade durations, saccade amplitudes, blink rates and durations.

Having taken into account the variance explained by time windows, subjects and hazard perception clips, fixation durations were significantly shorter in the high compared to the low cognitive task demand condition (*b*= - 17.24, *SE*= 8.025; *t*= -2.15). Furthermore fixation durations were significantly longer during the period in which the hazard was on screen compared to both periods before (*b*= -18.87; *SE*= 3.22; *t*= -5.87) and after (*b*= -26.4; *SE*= 3.31; *t*= 7.98) the hazard was present. Results also indicated a significant interaction between cognitive load and the time window ($\chi 2$ (2)= 12.78; *p*= .002). This interaction was because the reduction in fixation durations resulting from increased cognitive load was greater when the hazard was present compared to before the hazard was present (*b*= 16.46; *SE*= 6.19; *t*= 2.66). Average fixation durations for high and low cognitive load can be seen for each time window in Table 3.

Analysis of fixation position variance along the x-axis indicated no significant main effect of cognitive load (*b*= 141.8; *SE*= 567.8; *t*= .25) but did suggest a significant reduction of spread when the hazard was present as compared to the period before (*b*= 7125.2; *SE*= 392.9; *t*= 18.13) and after (*b*= 4555.9; *SE*= 440.5; *t*= 10.34) the hazard was onscreen. However we found no interaction between time windows and cognitive load ($\chi 2$ (2) = 1.6; *p*= .45).

Participants made significantly fewer fixations during the period when the hazard was present as compared to both periods before (*b*= 20.91; *SE*= .93; *t*= 22.56) and after (*b*= 14.24; *SE*= .81; *t*= 17.49) the hazard was visible. However results indicated no significant main effect of cognitive load (*b*= -.05; *SE*= 1.13; *t*= -.047) and no interaction between time windows and cognitive load ($\chi2$ (2) = 2.7; *p*= .26). Saccade peak velocities were significantly faster in the high compared to the low cognitive task demand condition (*b*= .02; *SE*= .009; *t*= 2.2). Furthermore peak velocities were significantly slower when the hazard was present as compared to periods before (*b*= .09; SE= .004; *t*= 19.49) and after (*b*= .07; *SE*= .005; *t*= 14.58) the hazard was on screen. However we found no interaction between time windows and cognitive load ($\chi2$ (2) = 1.8; *p*= .41).

Saccade durations were not affected by cognitive load (*b*= 2.27; SE= *1*.62; *t*= 1.4), however saccade durations were shorter in the period when the hazard was visible as compared to periods before the appearance (*b*= 2.91; *SE*= .46; *t*= 6.38) and after the disappearance (*b*= 2.24; *SE*= .47; *t*= 4.77). We found no interaction between time windows and cognitive load ($\chi2$ (2) = .22; *p*= .89).

Analyses of saccade amplitudes showed no main effect of cognitive load (*b*= .11; *SE*= .085; *t*= 1.3). However amplitudes were significantly smaller in the period during which the hazard was onscreen as compared to the time windows before (*b*= .67; *SE*= .12; *t*= 5.46) and after (*b*= .59; *SE*= .11; *t*= 5.32) the hazard was visible. Furthermore there was no interaction between time windows and cognitive load ($\chi2$ (2) = 5.26; p= .072).

We found no significant main effect of cognitive load on blink durations (b= 27.98; SE= 16.55; t= 1.7). Furthermore there was no differences in blink durations between periods before and during the hazard was onscreen (*b*= 17.39; *SE*= 11.39; *t*= 1.53). However blink durations were significantly longer after the disappearance of the hazard compared to when the hazard was onscreen (*b*= 24.74; *SE*= 10.95; *t*= 2.26) but we found no interaction between time windows and cognitive load ($\chi2$ (2) = 1.7; p= .43).

Blink rates were higher in the high compared to the low cognitive load condition (*b*= .26; *SE*= .09; *t*= 2.81). Furthermore blink rates were significantly higher after the hazard had disappeared (*b*= .25; *SE*= .07; *t*= 3.59) in comparison to when it was present. However there was no difference between the periods before and during the hazard appearance (*b*= .08; *SE*= .08; *t*= 1.01). We found no interaction between time windows and cognitive load ($\chi2$ (2) = .59; p= .75).

A summary of average oculomotor metrics between high and low cognitive load conditions for each time window can be seen in Table 3.

Table 3, *Average Number of Fixations (NFix) per clip, Fixation Durations (Fix. Durs) in milliseconds, Saccade Amplitudes (Sacc. Amps) in degrees, Saccade Durations (Sacc. Durs) in milliseconds, Saccade Peak Velocities (Sacc. PVs) in degrees per second, horizontal spread of fixations (X/Y-position variance; in pixels), Blink Numbers (N.Blinks) per clip and Blink Durations (Blink Durs) in milliseconds between high and low cognitive load conditions for the time windows before during and after the hazard was on screen along with standard deviations (in parentheses).*

	Before		During		After	
	High	Low	High	Low	High	Low
Nfix.[2,3]	29.03	31.9	9.47	9.54	23.69	23.55
	(*14.23*)	(*15.1*)	(*5.9*)	(*5.7*)	(*12.9*)	(*12.8*)
Fix. Durs[1,2,3,4]	331.82	331.66	342.41	357.12	320.77	332.82
	(*187.3*)	(*173.97*)	(*195.44*)	(*192.97*)	(*183.48*)	(*176.35*)
Sacc. Amp [2,3]	2.75	2.78	2.16	2.03	2.6	2.62
	(*2.2*)	(*2.24*)	(*1.89*)	(*1.83*)	(*2.12*)	(*2.19*)
Sacc. Durs [2,3]	31.96	29.83	29.37	27.48	30.83	28.88
	(*30.3*)	(*18.95*)	(*35.72*)	(*24.2*)	(*25*)	(*17.1*)
Sacc. PV [1,2,3]	208.19	204.43	177.1	171.64	203.99	192.78
	(*119.79*)	(*114.17*)	(*110.56*)	*(110.49)*	(*120.24*)	(*115.22*)
X-Spread [2,3]	11729.05	12472	5231.94	5114.8	9611.41	9852.91
	(*8143.29*)	(*8492.86*)	(*5987.19*)	(*5588.47*)	(*6678.35*)	(*7151.25*)
N.Blinks [1,3]	1.22	.86	1.09	.83	1.34	1.09
	(*1.38*)	(*1.11*)	(*1.21*)	(*.96*)	(*1.31*)	(*1.08*)
Blink Durs [3]	198.36	185.96	182.33	149.78	192.44	200.57
	(*250.39*)	(*226.88*)	(*185.21*)	(*116.43*)	(*188.37*)	(*198.99*)

1 Denotes a significant main effect of cognitive load
2 Denotes a significant difference between periods before and during
3 Denotes a significant difference between periods during and after
4 Denotes a significant interaction between cognitive load and time window

Saccade peak velocities over time

Saccade peak velocities were analysed as a function of time on task between both high and low cognitive load conditions. To this effect an LMM model was tested with cognitive load, trial number and saccade number as fixed effects as well as two random factors for hazard perception clip and participant.

Peak velocities decreased as a function of saccade number (b= .0007; SE= .0001; t= -4.95) and trial number (b= .0009; SE= .0004; t= -2.03). However we found no interaction between either trial number (b= .0003; SE= .0006; t= -.56) or saccade number (b= .0002; SE= .0003; t= .69) and cognitive load.

Electrophysiological Metrics

Overall Frequency differences between conditions

Participants' grand average (GA) of mid-theta (4 – 7 Hz), alpha (8 -15 Hz Band) and low beta (16 – 24 Hz Band) frequency outputs were calculated for each electrode individually for both high and low cognitive load conditions for each 30s hazard perception clip. We found more theta activity at T8 ($t(15) = -2.69$; $p = .017$) and CP6 ($t(15) = -2.54$; $p = .023$) in the high compared to the low cognitive task demand condition. Furthermore results indicate a marginally significant increase in theta at Pz ($t(15) = -2.1$; $p = .053$) in the high compared to the low cognitive task demand condition. Overall alpha was significantly lower at C4 ($t(15) = 2.87$; $p = .012$) in the high compared to the low cognitive task demand condition. Low-Beta was significantly lower at Fz in the high compared to the low cognitive task demand condition ($t(16) = 2.2$; $p = .043$). Average tonic frequency differences can be seen for mid-theta in Figure 1, alpha in Figure 2 and low-beta in Figure 3.

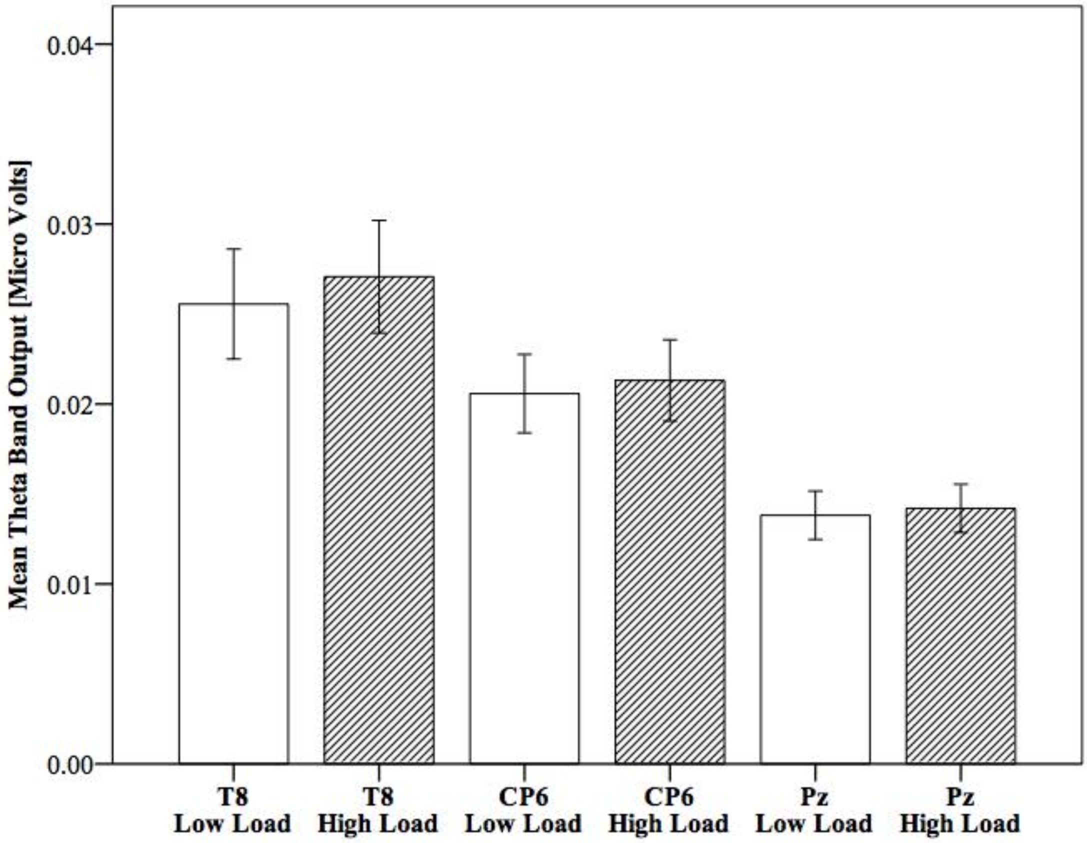


***Figure 1**, Bar graph showing average mid-theta (4-7 Hz) frequency activity at electrode sites T8, CP6 and Pz along with standard error bars for both high and low cognitive load conditions*

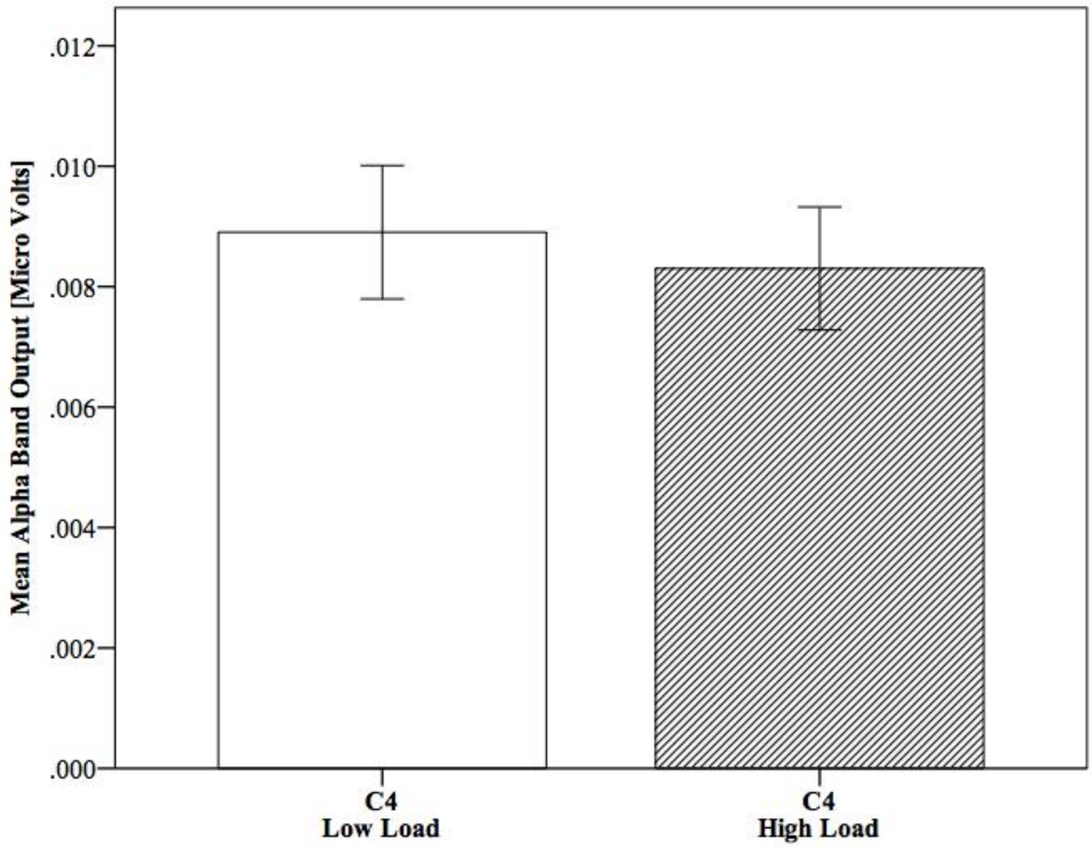


Figure 2*, Bar graph showing average alpha (8-15 Hz) frequency activity at electrode site C4 along with standard error bars for both high and low cognitive load conditions*

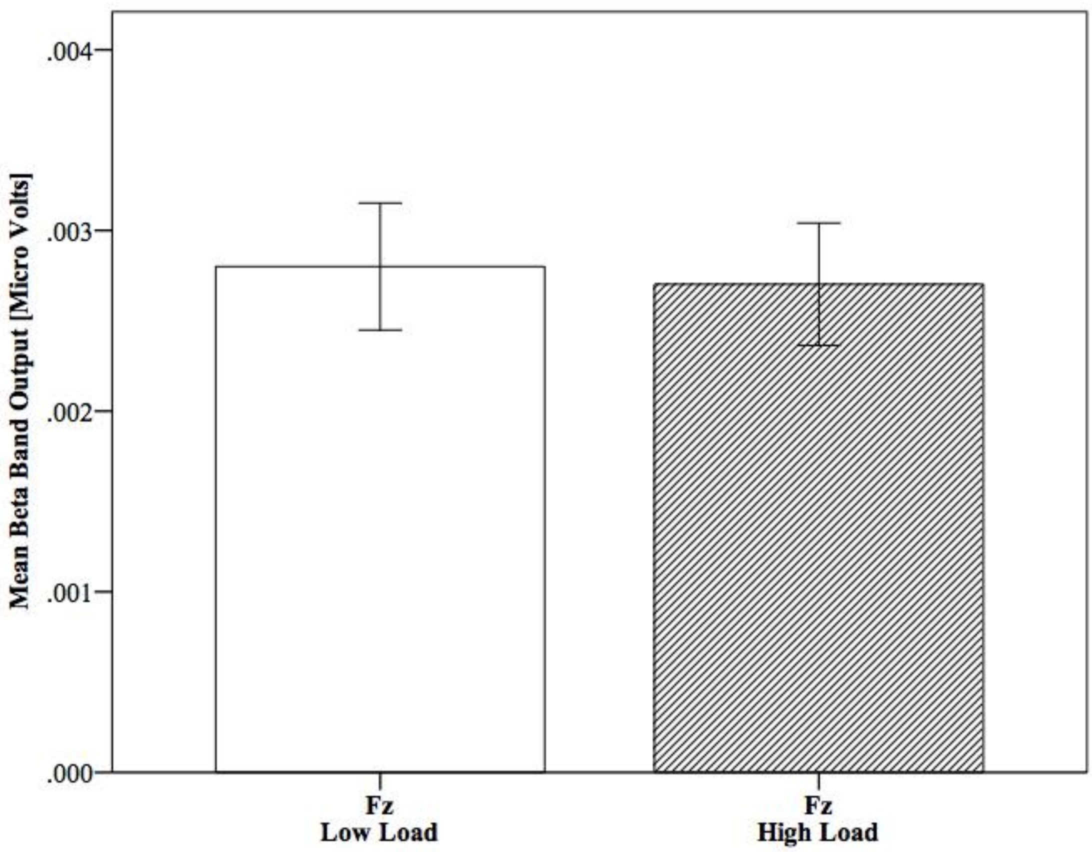


Figure 3*, Bar graph showing average low-beta (16-24 Hz) activity at electrode site Fz along with standard error bars for both high and low cognitive load conditions*

Frequency differences following Hazard Onset

Participants' grand average (GA) of high theta (6 – 10 Hz Bands), high alpha (12 – 15 Hz Band) and low beta (16 – 24 Hz Band) frequency outputs were calculated for each electrode individually for both high and low cognitive load conditions for the window 1000 ms prior to and 5000 ms following the hazard onset. There was a significant increase in theta at F7 ($t(16) = -2.21$; $p = .042$); P7 ($t(16) = 3.46$; $p = .003$) and P3 ($t(16) = -2.15$; $p = .046$) in the high compared to the low cognitive task demand condition. Furthermore there was a marginally significant increase in theta at CP5 ($t(16) = -2.09$; $p = .053$) in the high compared to the low load condition. High-Alpha was significantly higher in the high compared to the low cognitive task demand condition at CP1 ($t(16) = -2.94$; $p = .01$); CP2 ($t(16) = -2.59$; $p = .02$); CP5 ($t(16) = -2.32$; $p = .034$); CP6 ($t(16) = -3.98$; $p = .001$); P7 ($t(16) = -2.53$; $p = .023$); P2 ($t(16) = -3.33$; $p = .004$); P3 ($t(16) = -3.77$; $p = .002$); P4 ($t(16) = 4.19$; $p = .001$); P8 ($t(16) = -3.03$; $p = .008$); P03 ($t(16) = -2.93$: $p = .01$); PO4 ($t(16) = -2.63$; $p = .018$); O1 ($t(16) = -2.92$; $p = .01$); Oz ($t(16) = -2.43$; $p = .027$) and O2 ($t(16) = -2.43$; $p = .027$). Results also indicate significantly more low-beta at PO3 ($t(16) = -2.24$; $p = .04$); Oz ($t(16) = -2.14$; $p = .048$) and 02 ($t(16) = -2.26$; $p= .038$) in the high compared to the low cognitive task demand condition. Average frequency differences can be seen for high theta in Figure 4, high alpha in Figure 5 and low beta in Figure 6.

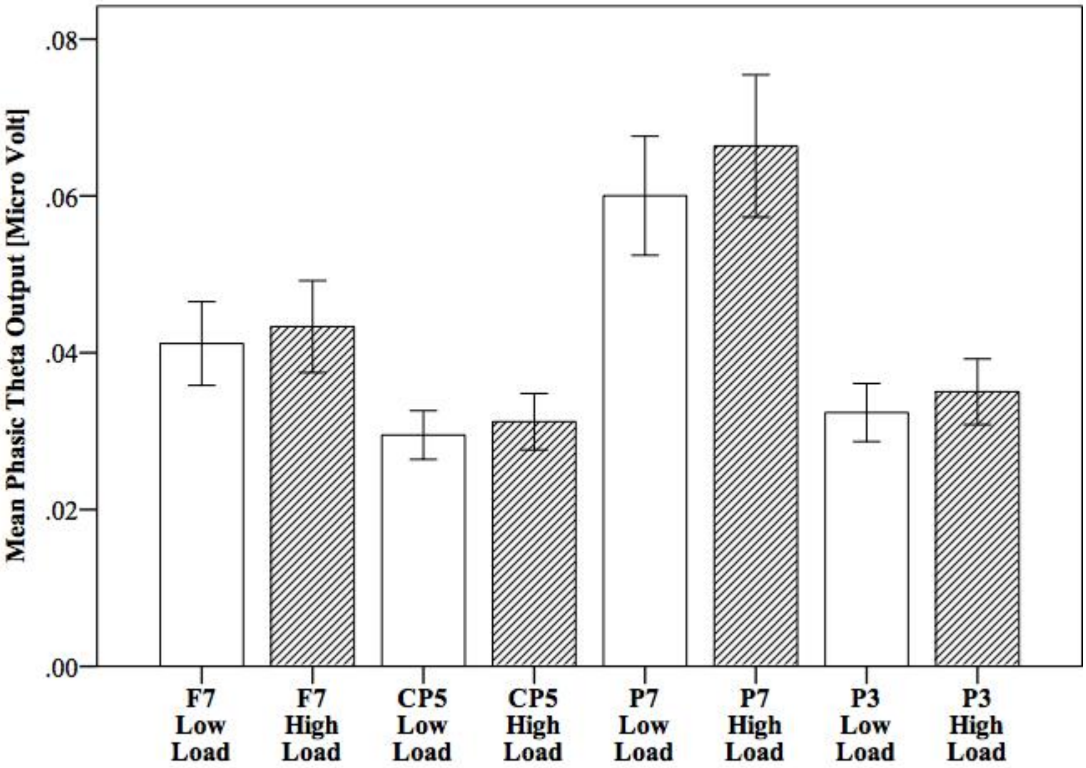


Figure 4, *Bar graph showing average phasic high-theta (6-10 Hz) output in response to the hazard onset at electrode sites F7. CP5, P7 and P3 for both high and low cognitive load conditions along with standard error bars*

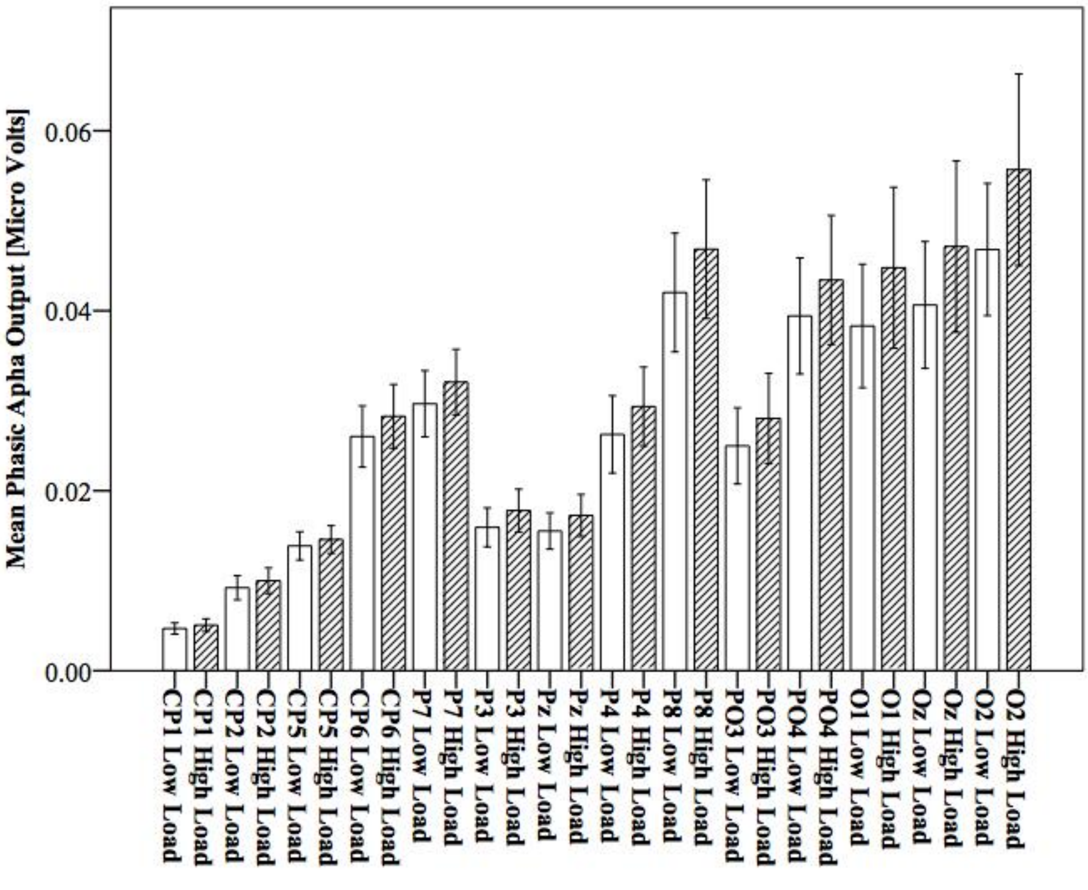


Figure 5, *Bar graph showing average phasic high-alpha (12-15 Hz) output in response to the hazard onset at electrode sites CP1, CP2, CP5, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz and 02 for both high and low cognitive load conditions along with standard error bars*

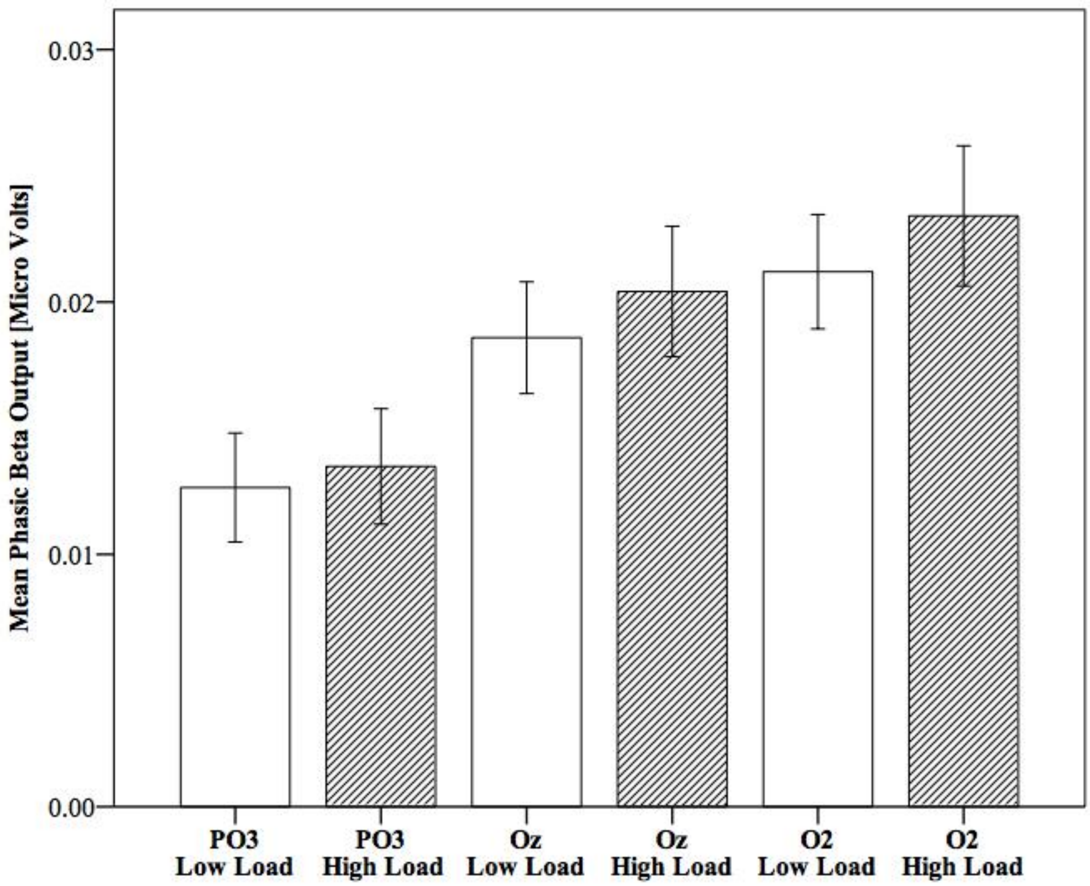


Figure 6, *Bar graph showing average phasic low-beta (16-24 Hz) output in response to the hazard onset at electrode sites PO3, Oz and O2 for both high and low cognitive load conditions along with standard error bars*

Differences in SPNs directly prior to the beginning of hazard perception trials

As SPNs depend on the association of two stimuli, the offset of the final word in the wordlist task was treated as the warning stimulus and the onset of the primary visual hazard perception task was treated as the imperative stimulus. In order to be able to record SPNs prior to the onset of the primary task, the time between the offset of the final word and the onset of the hazard perception clip was set to precisely 1500 ms. Stimulus event codes were used to segment a window 1500 ms prior to and 3000 ms following the beginning of each hazard perception trial. Within this SPN, GAs were created for the period 600 ms – 500 ms prior to the start of the hazard perception task

In this segment of the SPN average activity was significantly more negative going in the high compared to the low cognitive task demand condition at electrode sites FP1 ($t(15) = 2.14$; $p = .049$); F7 ($t(15) = 2.14$; $p = .049$) and FC6 ($t(15) = 2.53$; $p = .023$). Averages waveforms for these electrode can be seen along with a difference map plotting the cortical location of these significant differences in Figure 7.

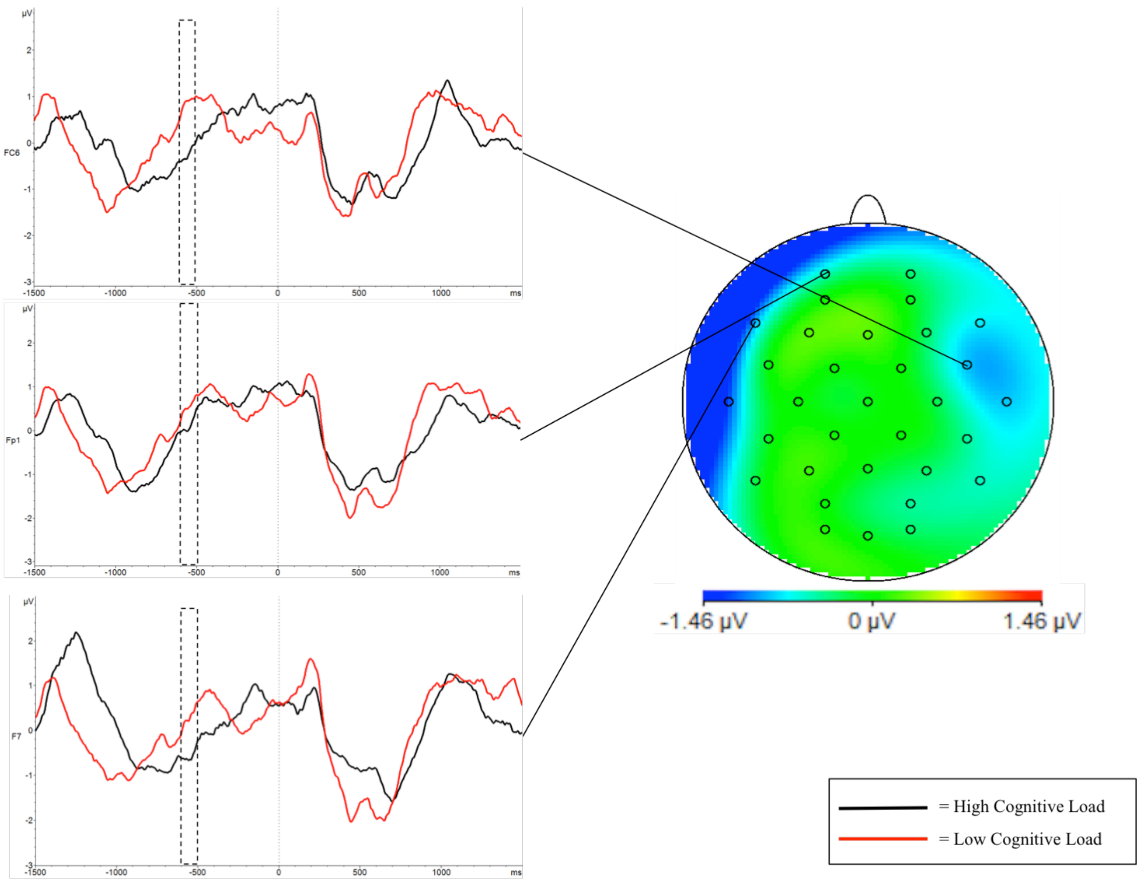


Figure 7, *Grand average difference waveforms at Fp1, F7 and FC6 along with average difference map between low and high cognitive load conditions. Differences between conditions were calculated in the highlighted area 600-500 ms prior to onset of the primary task, which is highlighted at 0 ms.*

Differences in SPNs directly prior to correct and incorrect responses

After stimulus event codes and behavioural event codes were used to segment a window 1000 ms prior to and 2000 ms following correct and incorrect responses, GAs were created for the epoch 600 ms – 500 ms prior to correct and incorrect response respectively. Results indicate that average activity was significantly more negative going in the low as compared to the high load condition at CP1 for both correct ($t(15) = -2.32$; $p = .035$) and incorrect responses ($t(15) = -2.14$; $p = .049$). There was however no significant difference in the average activity between the periods prior to correct and incorrect responses in either high ($t(15) = -1.03$; $p = .32$) or low ($t(15) = -1.26$; $p = .23$) load conditions. Average waveforms for these electrode sites can be seen along with a difference map for both correct and incorrect responses in Figure 8.

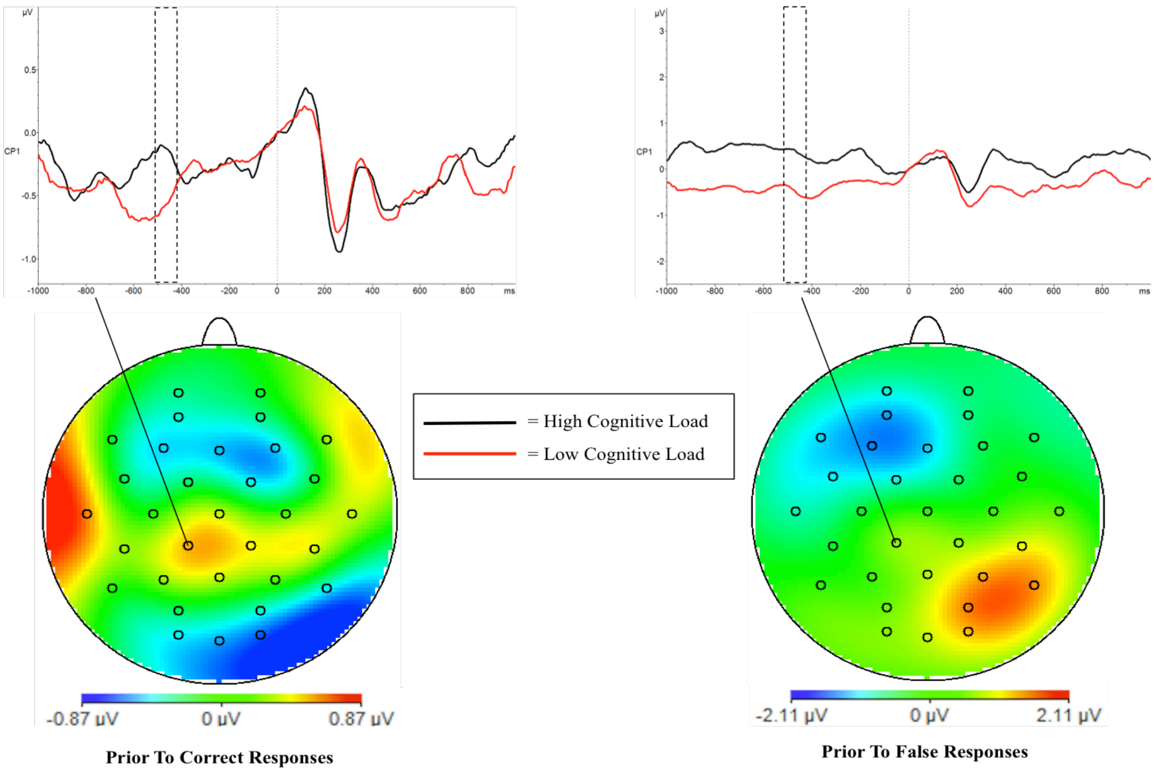


Figure 8, *Grand average difference waveforms at CP1 along with average difference maps between low and high cognitive load conditions for both correct and incorrect responses. Differences between conditions were calculated in the highlighted area 600-500 ms prior to button press responses, which are highlighted at 0 ms.*

Differences in activity after correct and incorrect responses

After stimulus event codes and behavioural event codes were used to segment windows 500 ms prior to and 1000 ms after correct and incorrect responses, collapsed GAs were created for the epoch 200 ms – 400 ms after correct and incorrect responses respectively. We found significantly more negative activity in high compared to the low cognitive task demand condition at electrode sites P7 (t(15) = 2.57; p = .021); Pz (t(15) = 2.84; p = .012), O1 (t(15) = 2.49; p = .025); Oz (t(15) = 2.45; p = .027); PO4 (t(15) = 2.17; p = .046); CP2 (t(15) = 3.21; p = .006); CP6 (t(15) = 2.21; p = .043). Conversely, results also suggest more negative going activity in the low compared to the high cognitive task demand condition at Fz (t(15) = -2.26; p = .039); F3 (t(15) = -3.99; p = .001) and FC1 (t(15) = -2.24; p = .041). However, for the same epoch following incorrect responses (false positives), there were no significant differences at any of the 32 electrode sites. Average waveforms for significantly differing electrode sites 200-400 ms after correct responses can be seen along with a difference map in Figure 9.

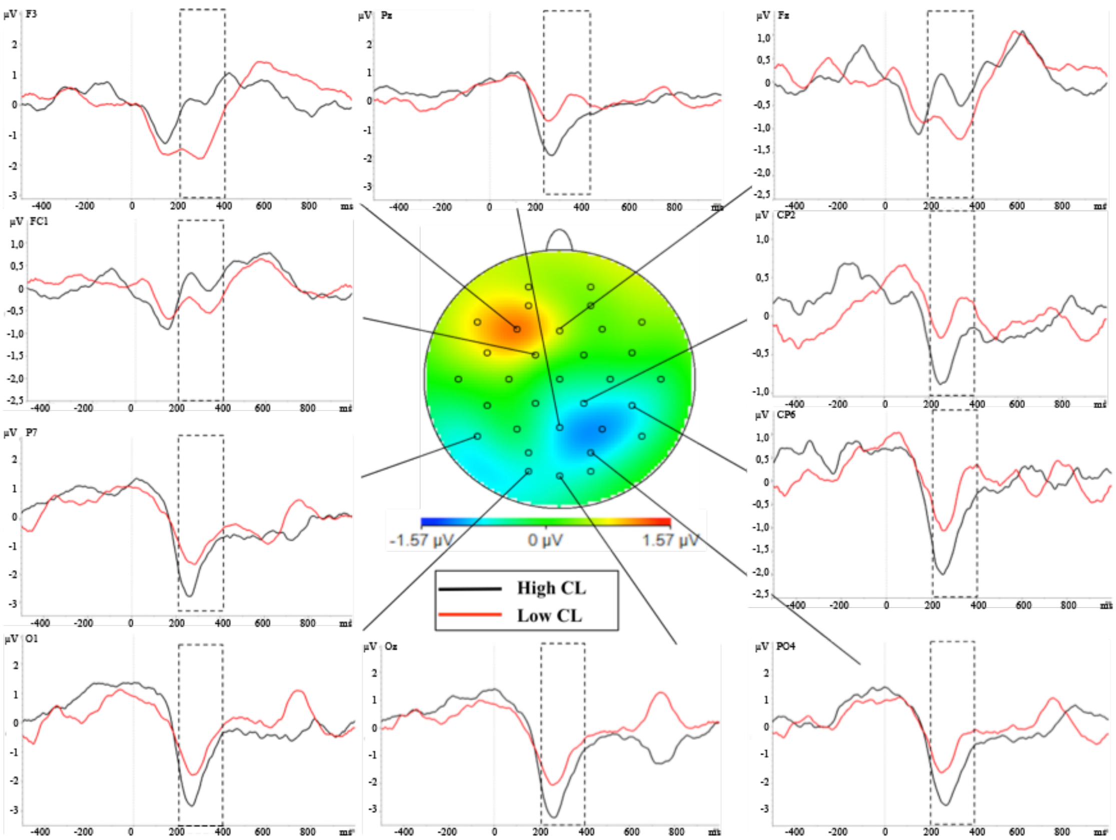


Figure 9, *Grand average difference waveforms at F3, FC1, P3, O1, Oz, PO4, CP6, CP2, Fz and Pz along with average difference map between low (Low CL) and high cognitive load (High CL) conditions. Differences between conditions were calculated for the highlighted area 200-400 ms after correct responses, which occurred at 0 ms*

Differences in fixation event-related potentials (fERPs)

After fixation event codes were used to segment windows 150 ms prior to and 600 ms following fixations, GAs were created for the epoch 50 ms – 150 ms after each fixation onset. Results indicate that average activity was significantly more negative in the high compared to the low cognitive load condition at electrode sites T7 ($t(16) = 3.09$, $p = .007$), P3 ($t(16) = 3.47$; $p = .003$); PO3 ($t(16) = 2.48$; $p = .025$) ; O1 ($t(16) = 2.14$; $p = .049$) and marginally at Oz ($t(16) = 2.11$; $p = .051$). Furthermore after GAs were calculated for the epoch 0 ms – 200 ms after fixation onset, results indicate a significantly more positive going activity at electrode site FC2 ($t(15) = -3.18$; $p = .006$). Location of differences as well as differences in fERPs between high and low load conditions can be seen in Figure 10.

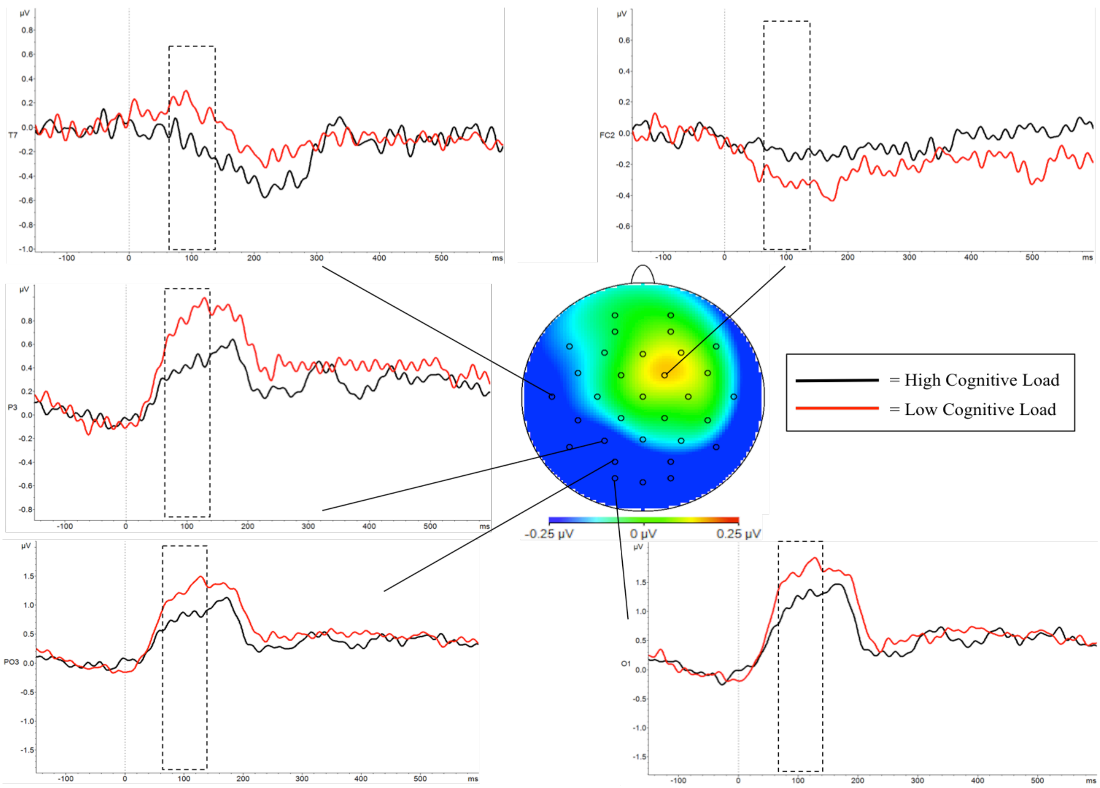


Figure 10, *Grand average difference waveforms at T7, P3, PO3, O1 and FC2 along with average difference map between low and high cognitive load conditions. Differences between conditions were calculated in the highlighted area 50-150 ms after each fixation onset, which is highlighted at 0 ms.*

Discussion

In order to examine the interaction between secondary and primary task demands, the current experiment considered the effects of secondary cognitive task demand on behavioural, oculomotor and electrophysiological measures across three different time periods within a modified hazard perception task. Secondary cognitive task demand was considered high on trials in which participants were presented with a 10-item wordlist prior to the start of a 30-second hazard perception clip. Hazard perception clips were shortened to 30-seconds in order to reduce variability of visual load across the different clips. Although behavioural measures were not negatively affected by the introduction of a secondary cognitive task, oculomotor and electrophysiological metrics did show changes consistent with cognitive distraction. Within real life settings, these results imply that changes in eye movements and neurophysiology may be able to detect cognitive preoccupation in the absence of an increase in crash risk.

Behavioural consequences of distraction

Behavioural results indicated that reaction times and false responses were not significantly negatively affected by the inclusion of a secondary cognitive task. We argued that shortening the hazard perception clip reduced the variation of visual task demand across clips but also significantly reduced primary task uncertainty. A typical hazard perception clip may contain a number of potential hazards that ultimately do not turn out to be hazardous. However reducing the original clip length in such a way as to only include one clearly identifiable hazard (and no potential hazards) may well have resulted in the primary task being easy enough for participants to be able to simultaneously process both primary and secondary tasks. This was also supported by the fact that not a single participant missed a single hazard (no missing responses in either condition).

However, despite there being no significant effect of load on reaction times and false responses, analyses of eye movements and electrophysiology indicated that previously identified signatures of distraction were sensitive to changes in cognitive task demand. A major consideration for potential markers of distraction is their ability to identify increases in crash risk before the actual crash occurs (Liang, Reyes & Lee, 2007). Therefore the observation that oculomotor and electrophysiological metrics are susceptible to variations in cognitive task demand although no increases in reaction times, false responses and missing responses were found is of great interest.

In real-life driving and in simulated driving increased secondary demand typically results in compensatory behaviour in the primary task (Antin et al., 1990; Curry Hieatt, & Wilde, 1975). This compensatory behaviour most likely frees-up cognitive capacities in order to process the more difficult primary task, or simultaneously process two-tasks. Models of executive control postulate the flexible mediation of cognitive resources depending on perceptual input (e.g., Shallice & Burgess, 1993). These models predict that when the driving task is easy, the primary task is processed primarily by automatic schema thus freeing-up more high-level executive functions such as working memory which can be devoted to the secondary task. However when the primary task becomes difficult, supervisory attentional systems are thought to regulate the allocation of resources in such a manner that the primary task receives priority. This results in primary task performance being less susceptible to increases in secondary task demand. Therefore analysing the susceptibility of oculomotor metrics to variations in secondary cognitive task demand across different time periods in the hazard perception clip may indicate which part of the primary task was perceived as most demanding.

The effect of distraction on oculomotor metrics

Overall analyses of eye movements between high and low load conditions indicated that saccade peak velocities were significantly faster when secondary cognitive task demand was high. Conversely results also suggested that peak velocities were significantly slower in the period during which the hazard was on screen compared both to periods before and after. Previous research has assessed the reliability of saccadic peak velocities as an indicator of mental workload (Di Stasi et al., 2010). In this study the authors manipulated mental workload by varying the degree of traffic density (more dense driving scenes being more mentally demanding) and results indicated a significant reduction of saccade peak velocities as primary task complexity increased. In the present experiment, mental workload was not manipulated in the primary task but rather in the form of a secondary cognitive task. At this stage it may be important to differentiate the term mental workload into two distinct categories: 1) visual task demand, and 2) cognitive task demand. Whereas we acknowledge that increasing the visual information of a driving scene can be considered “cognitively” demanding, the effects of manipulating primary and secondary task difficulty may have subtly different effects on eye movement behaviour. Results from this current study indicated a dissociation of the effects of primary and secondary task demand on saccade peak velocities: higher secondary cognitive task demand resulted in an increase in peak velocities whereas the presence of a hazard on screen resulted in a significant reduction of peak velocities.

It should be noted however that although saccade amplitudes and saccade durations were not affected by cognitive task demand, results revealed a significant reduction in these measures during the time window in which the hazard was present. This means to say that a reduction of saccade peak velocities during the hazard window was likely due to a significant reduction of saccade amplitudes (Bahill et al., 1975). However in our overall analyses, the increase in saccade peak velocities resulting from variations in secondary cognitive task demand were not associated with changes in amplitudes or durations. Therefore it seems that increases in saccade peak velocities were likely to be a result of the variation in secondary cognitive task demand and not an associated by-product of changes in saccade amplitudes or durations.

Furthermore, results indicated that saccade peak velocities decreased as a function of saccade number and trial number. This indicates that although increased cognitive task demand resulted in an increase in peak velocities, the longer participants performed the task the slower peak velocities became. Previous research has interpreted the decrease in peak velocities as a function of time on task as a measure of mental fatigue (Galley 1993, Di Stasi, 2012). These findings demonstrate that saccade peak velocities are sensitive to changes in secondary cognitive task demand as well as time on task and as such could provide a basis of monitoring changes in drivers' mental processes in real time. As saccade peak velocity models in our analyses included saccade amplitude as a fixed effect, the overall change in peak velocities as well as the change in peak velocities over time cannot be accounted for on the basis of changes in saccade amplitude.

One of the most consistent findings in simulated and real-world driving research is that the introduction of a secondary cognitive task results in the reduction of spread or a narrowing of fixations towards the centre of the road (Reimer, 2009; Victor, Harbluk & Engström, 2005). It could be argued that reducing the spread of fixations towards the centre of the road and thus restricting inspection of the scene, drivers may be attempting to free up cognitive resources engaged by the primary task- in order to simultaneously process the secondary task. Furthermore in tasks that are not self-paced, such as the hazard perception task, compensatory behaviour may be reflected by more subtle changes in viewing behaviour such as in the spread of fixations. As the reduction of spread in this current experiment did not reach significance it could be argued that this was a reflection of the fact that the primary hazard perception task was easier in this study, which is most likely attributable to the shortening of the original videos to 30-seconds. Although results indicated no significant reduction of the spread of fixations, averages revealed a reduction in horizontal position variance, which was in the same direction as previous research.

Despite the spread of fixations not being significantly affected by cognitive task demand, results indicated a significant reduction of the horizontal fixation position variance during the time in which the hazard was on screen, irrespective of secondary cognitive load. This was most likely due to fact that participants were monitoring the potential hazard once it had appeared on screen, thus most fixations would fall on and around the target. This is supported by an increase in fixation durations, shorter saccade amplitudes and saccade duration as well as fewer fixation numbers within the hazard period as compared to periods before and after the hazard was visible.

Fixation durations prior to the hazard onset were longer when secondary cognitive load was high. We found interactions between the time windows 'before' and 'during' as well as between the time windows 'during' and 'after' the hazard was on screen. This interaction was due to cognitive load having the opposite effect on fixation durations prior to the appearance of the hazard compared to during and after the hazard had disappeared. A possible interpretation may be that subjects were performing two different types of tasks when looking for and monitoring a potential hazard. The interaction between load and time window suggests that secondary cognitive task demand had a different effect during different periods of the hazard perception clip.

Both patterns of results could be explained within a compensatory behaviour framework. In general longer fixation durations have been thought to reflect primary task difficulty, in reading for instance, more difficult words are fixated upon longer (Rayner, 1998**).** Results from this current study seem to suggest that the appearance of the hazard in the clip results in a different kind of processing of the visual scene. Longer fixation durations during this period may reflect more effortful processing involved in monitoring the potential hazard in order to be able to react to the hazard onset in an appropriate and timely manner. Conversely the reduction in fixation durations as a consequence of increased secondary cognitive task demand may reflect a reduction in resources devoted to the processing of the primary task. This, in turn, could potentially free up cognitive resources necessary to compute both dual tasks simultaneously.

Analysis of blink frequencies and durations for the full 30-second hazard perception clips revealed a significant increase in the amount but not in the duration of blinks. This finding is in support of previous literature, which suggests that blink rates increase as a function of cognitive task demand (Ahlstrom & Friedman-Berg, 2006) whereas blink durations decrease as a function of visual task demand (Recarte et al., 2008; Veltman & Gaillard, 1996). The dissociation between the effects of visual and cognitive task demand on blink durations and frequencies is interesting as changes in these particular metrics could in future potentially be used to detect a driver’s current level of both cognitive and visual distraction.

Results from this current study indicated a significant increase in blink durations and blink rates after the hazard had disappeared from the screen. Fogarty & Stern (1989) have argued that changes in blink rates and durations are most likely a result of a compensatory mechanism designed to cope with the increase in task demand. This blink inhibition argument is supported by more recent research by

Siveraag and Stern (2000), which demonstrated that blink rates decreased as visual task complexity increased. Results from this current study confirmed that blink durations were shorter and blinks were less frequent during the period in which the hazard was visible compared to the period after it had disappeared. These results seem to support the blink inhibition hypothesis. However over the entire duration of a hazard perception clip an increase in secondary cognitive task demand resulted in a significant increase in blink rates. As the closing of the eyes during blinking temporarily restricts the amount of visual information entering the brain, it could be argued that increasing blink rates in response to increases in cognitive load may be a compensatory mechanism designed to free up resources in the primary task.

First saccade latency is a measure typically recorded in pro and antisaccade tasks as well as visual search tasks and is thought to reflect the speed at which new incoming visual information is being processed and appropriate saccade programs are written. In the current experimental paradigm we included a gap of 1500 ms between the offset of the secondary wordlist and the onset of the primary hazard perception task. During this period, the visual scene was blank, thus alerting participants to and preparing them for the imminent onset of the primary task. Therefore we argue that first saccade latencies in this current experimental paradigm may reflect preparatory mechanisms occurring before the start of the primary hazard perception task. Results indicated significantly longer first saccade latencies in the high compared to the low cognitive load condition. It could be suggested that increased secondary task demand may be interfering with the preparatory mechanisms prior to the start of the primary task. To further investigate this interpretation, the amplitudes of SPNs in the period 1500 ms prior to the start of the primary task were analysed between high and low cognitive load conditions.

Electrophysiological consequences of distraction

Analyses of EEG data from this current experiment revealed that increased cognitive load was associated with 1) a significant reduction in SPN amplitudes 500-600 ms prior to both correct and incorrect behavioural responses over frontal, central and occipital sites; 2) a significant decrease in SPN amplitudes over frontal, temporal and parietal sites 500-600 ms before the onset of each video; 3) significantly higher tonic theta frequency power at temporal and central parietal sites; 4) less tonic alpha frequency band output at central sites, 5) less beta frequency band power at frontal sites; 6) significantly more event related theta frequency output at frontal, central and parietal sites in response to the hazard onset; 7) more alpha band power at sites across the cortex in response to the hazard onset; 8) increased beta frequency output in response to the hazard onset at occipital sites; 9) significantly more negative going amplitudes of ERPs following correct responses at parietal and occipital sites; 10) significantly more positive going amplitudes following correct responses at frontal electrode sites; 11) significantly more negative going amplitudes of *f*ERPs at temporal and occipital sites; and 12) more positive amplitudes of *f*ERPS at frontal sites.

Overall frequency differences calculated on the entire 30-second period of the hazard perception trials indicated that mid-theta was significantly higher at left temporal, left central parietal as well as central parietal sites in the high cognitive load condition. This is in line with previous research, which has indicated that increased theta band energy is evident during spatial working memory tasks (Gevins et al., 1997; Klimesch, 1999; Tesche & Karhu, 2000). Increases in theta band power output have also been linked with organizing multi-item working memory in non-spatial tasks (Raghavachari et al., 2001). Therefore results from this current experiment are in support of these previous studies, which have found increases in theta band energy at a large variety of different cortical sites. High alpha frequency was found to be significantly lower at left central sites and low-beta frequency was found to be significantly lower at central frontal electrodes in high compared to low cognitive load trials. It should be noted that although the differences in frequency outputs in this current study were significant, these differences were in fact very small. Therefore it is difficult to make any strong claims as to the causes of these frequency differences under these specific circumstances. Previous authors have argued that increased activity in the theta band most likely reflected greater cortical engagement in response to processing two tasks (Jensen & Tetsche, 2002). Furthermore greater frontal theta band output was thought to demonstrate the activation of neural networks associated with the allocation of attention relative to the target stimulus. Another observation has been that increases in frontal beta band power output appear to be time locked to the onset of the secondary cognitive task (Lin et al., 2011). Therefore differences in frequency metrics are thought to be indicative of processes related to a specific component of mental calculation. Current tonic frequency differences seem to support the hypothesis that increased mental workload results in an increase (synchronisation) of theta and a decrease (desynchronization) in the alpha frequency band across a variety of cortical sites.

Furthermore analyses of event related frequency differences directly after the hazard onset indicated significant increases in theta, alpha and beta band outputs. Previous research by Lin and colleagues (2011) has suggested that increases in beta frequency may be time locked to the onset of a secondary cognitive task. Results from this current study indicated that over the entire 30-second hazard perception clip, beta frequency output was significantly reduced in the high compared to the low cognitive task demand condition. However in the period directly after the hazard onset, we recorded significantly more event related beta band power. This suggests that event related increases in beta may not necessarily be time locked to the onset of a secondary task, but rather are associated with sudden changes in dual task processing demands more generally. It could for instance be argued that the onset of the hazard required a variety of higher-level executive functions such as decision-making and response selection which were not necessary during periods in which the hazard was not present and the visual scene was merely being monitored. Thus the onset of the hazard may have changed the way in which attention resources were being allocated between primary and secondary tasks. Whilst in general performing a secondary cognitive task resulted in increased theta and decreased alpha and beta frequency output (Lin, Chen, Ko & Wang, 2011), it could be argued that decreases in phasic beta may be related to event related changes in both primary and secondary task difficulty. Results from this study have shown that both tonic and phasic changes in frequency metrics may be of interest not only in assessing overall processing demands, but also in monitoring fluctuations in primary and secondary task difficulty.

Differences in SPN amplitudes prior to the beginning of each hazard perception clip may suggest to what extent preparatory processes were affected by increases in cognitive task demand. Previous research has examined amplitudes of SPN between two clearly identifiable stimuli: a warning (S1) and an imperative stimulus (S2) that requires a response. In this current experiment we examined SPNs both prior to the onset of the hazard perception clip as well as before participants' manual responses.

As previously mentioned, a 1500 ms blank period was inserted between the offset of the final word (S1) and the onset of the hazard perception clip (S2). Typically research has indicated that SPN responses are associated with processes of attention, expectancy and motivation (Walter et al., 1964; Irwin, Knott McAdam & Rebert, 1966, McCallum, 1969; Tecce & Sheff, 1969). Results from this current study demonstrated a significant reduction in SPN amplitudes in the high compared to the low secondary cognitive load condition 500-600 ms prior to the start of the primary task. These results are in support of previous research, which has indicated that amplitudes of SPNs are reduced by both endogenous and exogenous distractors (McCallum & Walter, 1968; Rousseau, Bostem & Dongier, 1968). It could be argued that the secondary cognitive task may be interfering with the preparatory processes between the offset of the wordlist and the onset of the hazard perception task. In addition to this, analyses of first saccade latencies indicated that subjects required significantly longer to initiate their first eye movement in the high compared to the low cognitive load condition. The combination of these two findings seems to indicate that the introduction of a secondary cognitive task may be interfering with participants' preparatory processes thus resulting in more time being necessary to initiate the first saccade within the primary task.

For the analyses of SPNs prior to correct and incorrect responses, the imperative stimulus was reverse engineered from participants' manual responses. This means to say that the imperative stimulus was defined by the subject's own decision that a stimulus in the visual scene required a manual response. Normal SPNs analyses require a warning and an imperative stimulus followed by a manual response. The reasoning in this current study was that if participants decided to make a manual response, there must have been a warning stimulus directly prior to this response. Therefore equally sized windows were created in the period prior to participant's button responses for analyses of SPNs. Results indicated significantly more negative fluctuating amplitudes in the low as compared to the high cognitive task demand condition at central parietal sites 500-600 ms prior to both correct and incorrect responses; in the opposite direction to that recorded prior to the onset of the hazard perception clip.

Research by Kornhuber and Deecke (1965), conducted shortly after Walter and colleagues' (1964) initial report on CNVs (now SPNs), demonstrated a slowly increasing surface-negative cortical potential beginning to rise 500-1000 ms prior to voluntary spontaneous hand or foot movements. This rise in potential peaks around the time of motor response (Walter, 1968) and has been coined *Bereitschaftspotential* (or readiness potential; Kornhuber & Deecke, 1965). It has been argued that SPN and readiness potential are similar yet separate phenomena as SPN are present without a motor response (Cant et al., 1967). This slow negative potential was later thought to represent a preparatory response and a readiness for movement (Vaughan et al., 1968). Gilden et al. (1966) argued that as the early negative shift of cortical potential resembled SPN and was recorded without a contingent warning signal, it may be an indicator of preparation for movement. In this current experiment, average waveforms prior to correct and incorrect responses show a slow negative potential beginning at 600 ms prior to and peaking around the time of subjects' motor responses (Figure 8), consistent with previous research. However this readiness potential is significantly more negative going in amplitude in the low as compared to the high cognitive task demand condition. Therefore the introduction of a secondary cognitive task was to some extent interfering with the preparatory responses prior to voluntary motor responses.

Following this we were interested in determining whether the reduction in preparatory processes prior to motor responses were reflected in differences in ERPs 200-400 ms following subjects button presses. EEG derived brain potentials that are associated with voluntary motor movements have been called motor activity-related cortical potentials (MRCP) and were first recorded by Bates (1951). Following correct responses high secondary cognitive task demand corresponded with significantly less negatively fluctuating ERPs at frontal and dorsolateral prefrontal (DLPFC) sites and significantly more negatively fluctuating ERPs at parietal and occipital sites. A negative deflection shortly after erroneous responses (e.g. Falkenstein et al., 1991; Gehring et al., 1993) has been called error-related negativity (ERN) and is thought to reflect an action monitoring function (e.g. Luu, Flaish & Tucher, 2000). However more recently studies have shown similar ERN activity following correct responses (correct response negativity - CRN). It was argued that ERN/CRN activity were associated with response comparison processes (Vidal et al., 2000) or emotional responses to the response (Luu et al., 2000) rather than processes relating to error monitoring. Amplitudes of CRNs are greater in high conflict trials when subjects were uncertain about their responses (Botvinick et al., 1999; Carter et al., 2000) thus indicating an involvement in error monitoring and response conflict resolution. Therefore an increase in CRN amplitudes following correct responses in the high cognitive load condition may suggest that subjects were less certain about their responses. This was most likely due to the fact that for the same time window processing at DLPFC sites was significantly reduced.

Increased usages of executive functions are associated with increased processing negativity in the DLPFC (Corbetta et al., 2008). Results from Experiment IV indicated that amplitudes of CRN following correct button presses were significantly less negative in the high compared to the low secondary cognitive task demand condition. The reduction in processing negativity at DLPFC sites 200-400 ms after correct responses may therefore be an indication of a reduction in processing in areas associated with executive functions. Taken together, the differences in ERPs following correct responses could indicate that secondary cognitive load resulted in shift in activity from areas associated with executive function to regions most commonly associated with error monitoring, suggesting that subjects were less certain about their responses, possibly due to a reduction in processes relating to executive function.

Previously, the electrophysiological correlates of cognitive processes have predominately been restricted to experimental paradigms in which the exploration of the visual information was highly controlled such as in visual pattern reversal (e.g., Kazai & Yagi, 2003) and word recognition (e.g., Baccino & Manunta, 2005) paradigms. It has been argued that monitoring electrophysiological activity during fixations provides insight into the self-paced acquisition of perceptual information within the visual scene. Research has indicated significantly reduced theta activity at occipital sites in high compared to low load conditions (Savage et al., 2013). The authors argued that this may be a reflection of reduced visual processing within the primary task and that the reduction in theta was most likely associated with the reduction of horizontal spread of fixations. In order to determine differences in visual processing in the current hazard perception study, we analysed differences in *f*ERPs for each fixation between high and low cognitive load conditions. Results indicated a significant decrease in the amplitudes of *f*ERPs at occipital, parietal and temporal sites and a significant increase in amplitudes at frontal-central electrodes 50-150 ms following fixation onsets. Reduced amplitudes of *f*ERPs at occipital sites seem to support previous interpretations that the incoming visual information is not being processed to the same extent as when full cognitive capacities are available. As frontal sites of the brain are associated with effortful cognitive processing (Lin et al., 2011), larger amplitudes of fERPs at these sites may be indicative of increases in cognitive effort required to process the visual input of each fixation. In line with previous research, results from this current study suggest that *f*ERPs may be useful in the assessment of cognitive processes (Baccino & Manunta, 2005).

Conclusions

The aim of the current study was to examine the susceptibility of behavioural, oculomotor and electrophysiological measures to increases in secondary cognitive task demand. Although behavioural metrics were not affected by cognitive load, previously identified markers of distraction were still susceptible to changes in secondary cognitive task demand.

Reducing the length of the primary hazard perception clips most likely resulted in the primary task being less demanding than the original full one minute clips as evidenced by the lack of missing responses. Interestingly this current study suggested that increases in secondary cognitive task demand were associated with changes in oculomotor and electrophysiological measures despite no adverse effects on behaviour being found. Therefore it could be argued that the discussed changes in eye movements and EEG metrics may be indicators of the compensatory control mechanisms designed to compute the secondary tasks whilst simultaneously maintaining primary task performance.

Analyses of eye movements across different periods within the hazard perception clip demonstrated that the appearance of the hazard led to a change in viewing behaviour, which was characterized by longer and fewer fixations as well as a reduction in horizontal position variance. Results demonstrated that when the hazard was on screen the susceptibility of eye movement measures to variations in cognitive load was significantly reduced. This may imply that the appearance of the hazard results in a change in the way in which participants were allocating cognitive resources to both primary and secondary tasks. This difference may be characterised in terms of searching for and monitoring a potential hazard. The reduction in susceptibility of eye movement measures to secondary task demand during the time period in which the hazard was present may indicate a prioritisation of primary task.

As models of executive function (e.g., Norman & Shallice, 1986; Corbetta et al., 2008) postulate a flexible mediation of cognitive resources depending on current task demands, it could be reasoned that monitoring a potential hazard which is present is perceived as more demanding in comparison to scanning the visual scene when no potential hazards were present.

One major consideration for meaningful markers of cognitive distraction within driving situations is the ability to detect an increase in crash risk before the crash actually occurs. As oculomotor and neurophysiological metrics were significantly affected by the introduction of a secondary cognitive task although no changes in behaviour were observed, results from this current study imply that specifically measures of saccadic peak velocities, blink rates, phasic and tonic theta, SPNs (both prior to the start of the primary task and prior to manual responses), ERPs following manual responses as well as *f*ERPS may be indicative of variations in cognitive task demand. Most importantly these metrics were sensitive to increases in cognitive load in the absence of any changes in behaviour.

Chapter VI – General Discussion – Conclusions

Introduction

Distraction during driving is one of the leading causes of traffic accidents and is a major contributor to on-road injury and mortality rates (Evans, 2004). The aim of this current thesis was to consider 1) whether oculomotor and electrophysiological metrics could act as markers of cognitive distraction; 2) whether decrements in hazard perception performance caused by secondary cognitive task demand are to some extent due to cognitive load interfering with processes of alerting, orienting, inhibitory control and visual search; 3) what elements of secondary conversation tasks have the greatest impact on hazard perception performance; and 4) whether previously identified markers of cognitive distraction are affected by primary task difficulty.

The aim of this current chapter is to summarize the findings from each individual experiment of this thesis and to discuss how these findings relate to our initial research questions. Next, the effects of cognitive load on each individual primary task will be compared and contrasted. Furthermore theoretical and practical implications will be discussed. Finally we will consider limitations of the current research and discuss recommendations for the future.

The effects of secondary cognitive task demand on processes of alerting, orienting and inhibitory control

Building on the observation that preoccupation impairs hazard perception in both real life and simulated situations (Sagberg & Bjørnskau, 2006, McKenna & Crick, 1997, Alm & Nilsson, 1994), the first experiment of this thesis considered whether observed decrements in hazard perception performance could in part be due to secondary cognitive task demand interfering with processes of orienting, alerting and inhibitory control. To this effect we examined the effect of Savage's et al. (2013) secondary cognitive task on participants pro- and antisaccade performance. Furthermore we were interested in determining whether the previously identified oculomotor signatures of cognitive task demand in video based tasks were present in these more low-level visual attention paradigms.

In both pro- and antisaccade tasks, distracted participants exhibited longer Reaction Times (RTs), Verification Times (VTs), Time To Hit (TTH) and first saccade latencies, a reduced gain, increased first saccade error rates as well as blink durations. Furthermore interactions between primary and secondary tasks on measures of RTs and VTs indicated that the effect of secondary cognitive load was greater in the pro- compared to the antisaccade task. In the prosaccade task, overall frequency differences in alpha, beta and theta ranges indicated a significant tonic reduction in frontal, central, parietal and occipital alpha and beta as well as a reduction in frontal theta. In the antisaccade task parietal alpha was lower when cognitive load was high. When subjects were distracted, average activity of fixation Event Related Potentials (*f*ERPs) in the prosaccade task were significantly more positive at central and parietal sites and more negative at frontal sites in the antisaccade task. Button press Event Related Potentials (ERPs) in the prosaccade task were significantly more negative at central and parietal sites and more positive at frontal and temporal sites in the antisaccade task when cognitive load was high.

Increased first saccade error rates in both the prosaccade and antisaccade tasks were considered as evidence that cognitive load was interfering with processes of orienting and inhibitory control respectively. Furthermore as previous research has argued that the disappearance of the central fixation cue can act as an alerting signal (Lorenz, Oonk, Barnes, & Hughes, 1995), significantly longer first saccade latencies in the high cognitive load condition suggested that processes relating to alerting were also negatively affected. Taken together the results from Experiment I of the current thesis indicated that increases in secondary cognitive load resulted in decrements in processes of alerting, orienting and inhibitory control. Furthermore increases in RTs were most likely a result of distraction interfering with processes prior to, during and following visual orienting.

The effects of secondary cognitive task demand on processes of visual search

The aims of Experiment II were 1) to determine whether decrements in hazard perception performance were to some extent due to increases in cognitive task demand interfering with processes of visual search; and 2) to examine the effects of secondary cognitive load on systematic components of saccade distributions within visual search. Previous research by Gilchrist and Harvey (2006) attempted to identify strategic components of eye movements during visual search in order to examine their changes as a result of varying structural consistency of the visual search array. In order to determine the effects of cognitive load on these strategic elements we paired Savage's et al. (2013) secondary cognitive with Gilchrist & Harvey's (2006) primary visual search task.

Previous research has demonstrated that additional secondary cognitive load increases response times in visual search tasks (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). In line with this, we found that when distracted participants' RTs were significantly longer in both structured and unstructured trials. This was most likely a result of increased first saccade latencies, fixation durations, number of fixations and re-fixations as well as VTs when secondary cognitive load was high. Furthermore, subjects were significantly worse at reaching a target absent decision in the high compared to the low cognitive task demand condition. As VTs could only be calculated in trials where a target was present, increased false responses in target absent trials may reflect differences in the processes after the termination of visual search (such as response selection) on trials where no target was present. Strategic components of search behaviour as described by Gilchrist & Harvey (2006) were affected by the structure of the array as well as by secondary cognitive load. When cognitive task demand was high, participants made proportionally more fixations closer to the centre compared to the outer limits of the display. Importantly, distraction modulated strategic elements of visual search but did not eliminate them entirely.

Taken together results of Experiment II demonstrated that secondary cognitive task demand interfered with processes prior to (increased first saccade latencies) during (longer fixation durations, more fixations and re-fixations) and following the termination of visual search (longer VTs). Furthermore strategic elements of eye movements during visual search were altered but not eliminated. The change in scene viewing behaviour was marked by a narrowing of the spread of fixations towards the centre of the display.

Comparison of the component processes involved in secondary conversation tasks on hazard perception performance

Previous research has demonstrated that in terms of primary task performance deficits, there was no difference between hand-held and hands-free mobile phone devices. Therefore previous authors have argued that the cognitive load associated with conversing rather than the act of physically manipulating the mobile phone resulted in increased Missing Responses (MRs.) Furthermore results demonstrated that listening to the radio or listening to someone read a book did not interfere with RTs or MRs (Strayer et al., 2001).

Experiment III of the current thesis was aimed at determining the effects of the individual component processes of secondary conversation tasks on hazard perception performance. Specifically we were interested in comparing and contrasting the effects of working memory, language production and language processing on RTs, FRs and MRs in a video based hazard perception task. To this effect we compared and contrasted the effects of 1) a secondary wordlist working memory task presented prior to the onset of the primary task; 2) a secondary wordlist working memory task presented during the primary task; and 3) a secondary wordlist n-back1 task presented during the primary task on hazard perception performance.

We found that all three secondary tasks caused decrements in primary hazard perception performance. More interestingly however was that we found no difference between the different types of tasks in terms of the costs incurred to hazard perception performance. This indicated that over and above the working memory element, processes relating to language comprehension and production did not lead to a significant deterioration of hazard perception performance. Results from Experiment III are in support of previous research arguing that the leading cause of distraction associated with conversing is the increase in secondary cognitive task demand.

The susceptibility of oculomotor signatures of cognitive task demand in a hazard perception task during periods of target presence and absence

The aims of the final study of this thesis were to 1) consider whether cognitive distraction had an effect on fixation event related potentials (*f*ERPs) within a video based search task; and 2) to compare the susceptibility of previously identified oculomotor markers of distraction across three different periods within each clip (before, during and after the hazard was on screen). As the hazard perception task does not allow subjects to directly influence primary task difficulty (i.e. by slowing down driving speed), it was predicted that compensatory behaviour would be reflected in more subtle changes in viewing behaviour and electrophysiology.

We found significantly faster peak velocities, more blinks and a reduced spread of fixations along the x-axis when cognitive load was high. Furthermore the susceptibility of these measures to load was significantly reduced when a hazard was present compared to before and after it was on screen. This may indicate that subjects were performing two distinctly different types of visual processing when the hazard was visible compared to when no hazard was present.

Average EEG frequency output for the full 30-second hazard perception clip revealed significantly less central alpha, frontal beta and more central, parietal and temporal theta activity when secondary cognitive task demand was high. Event related frequency differences around the time of the hazard onset showed a significant increase in central, parietal and occipital alpha; parietal and occipital beta as well as frontal central and parietal theta output when participants were distracted.

When subjects were distracted, Stimulus Preceding Negativities (SPNs) were significantly more positive prior to the start of the primary task and correct and incorrect responses, indicating that cognitive load was to some extent interfering with preparatory processes. This was supported by significantly longer first saccade latencies measured from the onset of the primary task and differences in button press ERPs.

ERPs around the time of button presses indicated more positive activity at frontal sites and more negative activity at parietal and occipital sites. As frontal sites are associated with effortful, top down behaviour (e.g. Corbetta et al., 2008), more positive ERPs may indicate increased processing demands within areas of executive functions when secondary cognitive task demand was high. The occipital lobes are involved in visual processing and the parietal cortex plays a role in translating visual information into motor responses (Milner & Goodale, 2004). Therefore it could be speculated that reduced ERPs in these areas around the time of correct button press responses indicated a reduction in processes relating to visual information transformation and appropriate response selection.

In order to determine differences in visual processing in the current hazard perception study, we analysed differences in fERPs for each fixation between high and low cognitive load conditions. Results indicated a significant decrease in the amplitudes of *f*ERPs at occipital, parietal and temporal sites and a significant increase in amplitudes at frontal-central electrodes 50-150 ms following fixation onsets. Reduced amplitudes of fERPs at occipital sites seem to support previous interpretations (Savage et al., 2013) that the incoming visual information was not being processed to the same extent as when full cognitive capacities are available. Frontal sites of the brain are associated with effortful cognitive processing (Lin et al., 2011). As event related negativity at frontal sites of the brain is associated with effortful cognitive processing, more positive fERPs at these locations may be indicative of reduced processing (George et al., 1996) in areas linked to executive functions.

Most importantly was that these metrics were sensitive to increases in cognitive load in the absence of any changes in primary hazard perception task performance. This work suggests that these markers may in future be used to detect distraction prior to an increase in crash risk.

General Discussion

Driver cognitive distraction can have a multitude of causes including but not limited to the detrimental effects of conversing on hand-held and hands-free devices (Patten et al., 2004; Strayer & Drews, 2007), ruminating on a previous conversation (Savage, Potter & Tatler, 2013), mind wanderings (Cowley, 2013) and device induced distractions (Jacobson & Gostin, 2010, Strayer & Drews, 2007). Whereas the ultimate outcome of all different types of distraction is an increase in crash-risk the changes in the underlying mechanisms resulting from these different types of distraction are different (Regan, Lee & Young, 2008; Anstey et al., 2005). There has been a wealth of research devoted to the effects of conversing on a cell phone on a wide variety of driving performance measures, ranging from behavioural (Alm and Nilsson, 1994, Strayer and Drews, 2004) to oculomotor (Strayer, Drews & Johnston, 2003) and neurophysiological (Strayer & Drews, 2007, Lin et al., 2011, Wester et al., 2008). However there is surprisingly little research focussed on the period immediately following a telephone conversation. As previous work has provided evidence suggesting that the distraction caused by conversing on a mobile telephone is due to the cognitive demand of the conversation and not the physical manipulation of the telephone itself (Alm & Nillson, 1994; Strayer et al., 2001), it is feasible to argue that for a period following a particularly stressful or engaging conversation drivers will still be distracted.

In order to determine which aspect of secondary conversation tasks had the greatest effect on hazard perception performance, Experiment III compared processes of secondary cognitive task demand, language production and processing on primary task performance. We found that over and above the deficits caused by a secondary cognitive task, processes relating to language production and processing did not result in an increase in the detriments observed in hazard perception performance. These findings are in line with previous research, which had argued that secondary cognitive task demand increases are the main cause of distraction during conversation tasks (Strayer et al., 2001).

To further investigate the effect of secondary cognitive task demand on processes crucial to hazard perception performance, Experiments I & II of this current thesis replicated Savage's et al. (2013) secondary cognitive load paradigm on tasks designed to measure the speed and efficiency of orienting, alerting, inhibitory control and visual search. We considered the possibility that the detriments observed in a complex video based hazard perception task might be due to cognitive load interfering with one or more of its individual component processes. Results from Experiments I

& II confirm that secondary cognitive task demand interferes with processes of orienting, inhibitory control and strategic elements of visual search.

Increases in RTs in both tasks were most likely to some extent an association-by-product of increases in first saccade latencies, first saccade error rates and VTs. Time to hit on the other hand was invariably influenced by first saccade latencies and error rates. However, as VTs were measured between the final fixation upon the target placeholder and the following manual response, this metric was independent from increases in other measures. In pro/antisaccade and visual search tasks we found that cognitive load negatively affected all factors that contribute to the speed at which participants were able to make a manual response. This means to say that distraction resulted in an increase in the time it takes to find the target (Time to hit - first saccade latency, first saccade error rate) as well as the time it takes to decide that the fixated item is appropriate (VTs). In addition to this, in Experiment II participants made significantly more fixations and re-fixations, which invariably contributed to RTs.

Models of executive control (e.g.. Corbetta et al., 2008) have argued that the interference of secondary cognitive load can be attenuated when the primary task becomes more demanding. In Experiment I we found that the decrements in RTs and VTs caused by increases in secondary cognitive load were greater in the pro compared to the antisaccade task. This indicated that processes of inhibitory control involved in supressing reflexive saccades (antisaccade task) were most likely more cognitively demanding than reflexively orienting visual attention from one location to the next (prosaccade task). We did not find an interaction between the structure of the array and cognitive load on participants RTs and VTs in Experiment II. As set forward in Chapter III, reducing the structural consistency of the search array may not alter primary task demand, as the amount of visual information (i.e. the amount of distractor items and size of display) was not increased. In Experiment IV, manipulations in secondary cognitive load did not lead to an increase in RTs. This was most likely due to the fact that the primary hazard perception clips were reduced from their original length (1-minute) to 30-seconds in order to reduce variability in visual load. Experiment IV utilized a similar "wordlist before" secondary task employed in Experiment III, which resulted in significant deficits to hazard perception performance. Therefore it was not the change in secondary tasks (from Experiments I & II) that resulted in primary task performance not being influenced, but rather the reduction of uncertainty within the primary hazard perception task.

The effects of load on processes of searching for versus monitoring a potential hazard

In order to determine the effects of the content of videos on subjects' visual processing, Experiment IV examined the susceptibility of previously identified markers of cognitive distraction between periods in which the hazard was present and absent.

In standard visual search tasks (such as Experiment II) participants are asked to make a target present/absent decision. Different mechanisms may be involved in target absent compared to target present decisions (Chun & Wolfe, 1996). Therefore on half of trials subjects are searching for a target when none is present. We argue that processes during hazard perception are similar in that some of the times during the primary task participants are searching for a hazard that is not present, whilst other times it is.

It is acknowledged that visual search in hazard perception tasks is somewhat different than low-level visual search paradigms and that searching through videos may also engage different strategies compared to searching through static scenes. Nonetheless the distinction between searching for a hazard and monitoring a potential hazard is an important one and none of the Experiments of this current thesis manipulated primary task demands. Therefore by analysing eye movements between high and low load conditions, as well as across periods during which hazards were present and not present, we were able to examine the interaction between primary visual and secondary cognitive task demands on subjects' visual processing.

When cognitive load was high, measured over the entire 30-second durations of the hazard perception clips blink rates were higher, saccade peak velocities were faster, fixation durations were longer and the spread of fixations was marginally reduced. When the target was on screen this significant main effect of load disappeared for all four measures. This was most likely a result of most fixations falling on or around the hazard once it had appeared on screen. This was taken as evidence that subjects may have been performing two distinctly separate types of processing during the primary hazard perception task. When no hazard is present cognitive load affects how we search for objects in our environment, however when a hazard is present, processing priorities seem to change. This shift in processing priorities is supported by models of executive function with posit that secondary cognitive distraction can be attenuated when primary tasks demands change relative to the goal of the observer (Corbetta, Patel & Schulman, 2008). Furthermore results from Experiments I & II indicated that when distracted, VTs were significantly longer. Taken together this suggests that distraction interferes with processes relating to searching for as well as verifying or monitoring potential targets.

The presence of the hazard also had a significant main effect on measures that did not exhibit an effect of secondary cognitive task demand: saccade amplitudes and durations were smaller and blink durations were shorter. Changes in saccade amplitudes and durations were most likely directly related to the fact that most fixations were landing on or around the target. However decreases in blink durations have typically been associated with increased visual task demand (Siveraag & Stern, 2000), which seems to be supported by our own finings. Experiment IV demonstrated that secondary cognitive and primary visual task demands can have different and dissociable effects on eye movement behaviour, specifically on blink rates and blink durations.

Blink Rates and Durations

In both Experiments II and IV blink rates were significantly higher when cognitive task demand was high. In contrast to this we found no effect of load on blink rates in Experiment I.

Previous research has suggested that blink rates are a good indicator of mental fatigue and workload (Fukuda, Stern, Brown & Russo, 2005; Stern, Boyer & Schroeder, 1994). One possible explanation as to why we found no effects of load on blink rates during both pro- and antisaccade tasks was because of the structure of the primary task itself. Typically one trial within Experiment I lasted no longer than 4 seconds whereas search trials lasted until the target was found (or its absence confirmed) and trials in Experiment IV lasted 30 seconds. The shortness of the trials in Experiment I most likely allowed subjects to supress blinking until the moment they responded thus fewer blinks fell into the actual period of pro- antisaccade trials. As trials in Experiment II and IV were longer, blinks could not be supressed for a prolonged period of time. This is in line with previous research that has argued that inhibition of blinks can occur in tasks when visual perception is essential so as to prevent the loss of important information. However blink inhibition requires cognitive resources. As time goes on, these mental resources become fatigued resulting in an increase in blink rates as a function of time on task. Blink inhibition interpretations (Rescartes et al., 2008) can therefore account both for an increase in blink rates when cognitive load is high as well as an increase in blink rates as a function of time on task. As blink rates were affected by cognitive workload in both low-level visual search (Experiment II) and complex video based tasks (Experiment IV), the current thesis indicates that blink rates may be a reliable indicator of cognitive workload regardless of the primary task. In addition to this, we found no effect of cognitive workload on blink durations. Previous research has demonstrated that blink durations decrease as primary visual task demand increases (Siveraag & Stern, 2000). Taken together these results indicate that blink durations and blink rates may be reliable indicators of visual and secondary cognitive task demand respectively.

Processes of orienting, alerting and inhibitory control

The prosaccade task requires subjects to reflexively orient their exogenous visual attention to a sudden onset target. Although this is a simple task, results from Experiment I of this current thesis suggested that when cognitive load was high, participants' first saccade error rates were increased. This demonstrates that secondary cognitive task demand was interfering with processes relating to the efficiency of orienting of visual attention.

In the antisaccade task participants are required to inhibit reflexive orienting to a sudden onset target in favour of programming a saccade to a placeholder, usually in a mirror location. When cognitive load was high, subjects made more first saccade error rates within the antisaccade tasks. Inhibitory control processes are thought to be effortful and time consuming (Hutton, 2008). People with higher working memory capacities typically exhibited fewer first saccade errors on both pro- and antisaccade tasks (Unsworth, Schrock & Engle, 2004) indicating that working memory processes are to some extent involved in inhibitory control processes. Results from Experiment I of this thesis therefore indicated that secondary cognitive load was interfering with processes of reflexive orienting and inhibitory control.

First saccade latencies following the target onset were significantly longer when cognitive load was high (in both pro and antisaccade tasks). As first saccade latencies are thought to reflect internally guided decision-making (Carpenter &

Williams, 1995) and preparatory processes two arguments may be put forward. Cognitive load may be interfering with processes of alerting or the disengaging of attention once the central fixation point has disappeared, which results in longer first saccade latencies when distracted. However as analyses of EEG metrics around the time of the offset of the central fixation cue (alerting signal) indicated no effect of cognitive load on participants alerting responses, an alternative explanation may be that cognitive load was interfering with decision making processes once the target had appeared. However in Experiment IV, we found a significant decrease in preparatory processes prior to the onset of the primary task when cognitive load was high (indexed by significantly more positive SPNs), which were also associated with a significant increase in first saccade latencies. Therefore it seems that secondary cognitive task demand may have also been interfering with preparatory processes prior to the start of the primary task in Experiment IV.

Across all three experiments in which eye movements were recorded (Experiments I, II & IV), increases in secondary cognitive task demand resulted in a reduction in the spread of fixations along the horizontal axis. In Experiment I participants were required to make a saccade of a specified size. The introduction of a secondary cognitive task resulted in reduced first saccade gain, which suggested that saccade landing points were not being calculated appropriately. In Experiment II both structure and load affected the distribution of saccades and the spread of fixations along the x-axis. As saliency based models (e.g., Itti & Koch, 2002) state that fixation locations are determined solely by the properties of the scene, these models would have predicted an effect of structure but not of cognitive load on the spread of fixations. In driving, research by Harbluk, Noy & Eizenman (2002) demonstrated that the percentage of time spent fixating around the centre of the road varied as a function of secondary cognitive task complexity: more complex tasks led to increased gaze concentration towards the centre of the road (Reimer, 2009; Victor, Harbluk & Engström, 2005). In Experiment IV we found a significant reduction in the spread of fixations along the x-axis when secondary cognitive load was high. The susceptibility of the spread of fixations to secondary cognitive task demand was however only present when no clear target was on screen. When a target was present there was no effect of load on the spread of fixations, most likely due to the fact that most fixations were falling on or around the hazard. The spread of fixations reveals how much of the environment was being explored (Crundall & Underwood, 1998). It could be speculated that the reduction in the exploration of the environment, when cognitive load is high, may be a strategy aimed at freeing up cognitive resources in order to compute both tasks. Results from Experiment II and IV of this thesis demonstrated that increased secondary cognitive load reduced the exploration of both low-level and complex visual scenes. As effects of cognitive load were similar across tasks that were visually completely different, we argue that the content of the scene is not the only factor that determines the distribution of fixations within our environment. This reduction in spread may be due to cognitive load interfering with the calculation of saccade end points as also found in Experiment I.

Saccade Peak Velocities

In Experiment I, the average gain of first saccades was significantly reduced when cognitive load was high, however first saccade peak velocities were not affected. Previous research has found faster peak velocities when secondary cognitive task demand was high (Savage, Potter & Tatler, 2013). Interestingly, in Experiment I we found no difference in first saccade peak velocities although gain was reduced. It could therefore be speculated that the velocities of first saccades were faster than they should be, given the reduction in gain.

Conversely in Experiment II we found that saccades peak velocities were significantly slower in the high compared to the low cognitive load condition. However, closer inspection revealed that when subjects were distracted, peak velocities decreased more rapidly over time than when cognitive load was low.

In Experiment IV saccade peak velocities were significantly faster when cognitive load was high. Therefore the effect of secondary cognitive task demand on saccade peak velocities was different across all three Experiments in which eye movements were measured. These differences most likely arose due to the different demands of the primary tasks. In Experiment I participants were required to make eye movements of a predefined size, in Experiment II subjects were presented with static scenes and in Experiment IV with video clips. Previous research has demonstrated that manipulating the visual information of a scene (e.g., increasing traffic density) resulted in slower saccade peak velocities (Di Stasi et al., 2010), indicating that this particular metric is not only sensitive to secondary (Thomas & Russo, 2007; Savage et al., 2013) but also primary task demands.

Saccade Peak Velocities over time

Previous research has demonstrated that peak velocities are affected by mental activation (App & Debus, 1998), alertness (Thomas & Russo, 2007) and fatigue (Grace et al., 2010; Zils et al., 2005, Schmidt et al., 1979) as well as decrease as a function of total time on task (Galley, 1993; DiStasi, 2012). Therefore we were particularly interested in examining any interaction between cognitive load and time on task on saccade peak velocities.

In Experiment I, we found a three-way interaction between trial number, type of task (pro or antisaccade) and cognitive load. This interaction was due to the fact that 1) peak velocities were generally slower in the anti compared to the prosaccade task and 2) because cognitive load had an opposite effect on peak velocities in the pro as compared to the antisaccade task. In the prosaccade task peak velocities were slightly faster when cognitive load was high, whereas in the antisaccade task peak velocities were slower when cognitive load was high. Peak velocities of correct antisaccades are slower than peak velocities of correct prosaccades (Hutton, 2008) however it is unclear as to why cognitive load should have an opposite effect on peak velocities depending on the type of primary task. It could be argued that secondary cognitive load was interfering with processes relating to executive functions such as inhibitory control, which were necessary to maintain primary task performance. Therefore when both primary and secondary tasks draw upon executive functions such as working memory, task switching and inhibitory control, the peak velocity with which eyes were moved was slowest. In line with previous research peak velocities did reduce as a function of trial number. More interestingly however was that the rate at which peak velocities decreased was faster when secondary cognitive task demand was high. Similarly in Experiment II we found a difference in the development of peak velocities over time between high and low cognitive load conditions. For both target present and absent trials peak velocities decreased as a function of total time on task only when cognitive load was high and slightly increased when cognitive load was low.

Finally in Experiment IV we found that peak velocities decreased as a function of saccade number and trial number but found no interaction between our time measures and secondary cognitive load. However this may in part be due to the final Experiment making use of hazard perception clips which were half the length of previous primary tasks of this current thesis.

Two conclusions can be drawn from the presented data: 1) results from both hazard perception studies suggested that when viewing videos and secondary cognitive task demand was high, participant’s saccade peak velocities were faster; and

2) in both low level visual paradigms (Experiments I & II) saccade peak velocities decreased faster when secondary cognitive load was high. This suggests that peak velocities are sensitive to changes in visual load and mental processing (or activation) relating to both primary and secondary task demands. Taken together it becomes clear that more work is needed to tease apart the effects of mental activation caused by both primary and secondary task manipulations and fatigue caused by time on task.

EEG Frequency Measures

EEG power is thought to be indicative of the amount of neurons firing together (Klimesch, 1999) and as such reflects the performance or capacity of information processing (Klimesch, 2012). Typically research has demonstrated that task demand increases result in a decrease in alpha in and an increase in theta frequency output. Beta frequency band activity is considered a marker of cortical arousal (Niedermeyer, 1999) and multimodal integration across large areas of the cortex (von Stein et al., 1999). Previous research has speculated that theta and beta band activity in frontal areas of the brain are associated with cognitive processes such as decision-making, working memory, problem solving and judgment (Lin et al., 2011).

In this current thesis frequency outputs were analysed in both pro- and antisaccade tasks (Experiment I) as well as in our final hazard perception study (Experiment IV). Over all three tasks increased cognitive load resulted in a desynchronization of alpha, which indicated that this particular frequency band may be a good indicator of secondary cognitive task demand, regardless of the type of primary task. When cognitive load was high, beta frequency power was reduced in the prosaccade and in the hazard perception task, however we found no differences in the antisaccade task. This may indicate that processes relating to inhibitory control were attenuating the effects of distraction on overall beta frequency output. We found opposite effects of load on theta band power for both hazard perception and prosaccade tasks. In the prosaccade task distraction resulted in a decrease in theta, whereas in the hazard perception task it resulted in an increase. Results from Experiment IV of this current thesis support previous research, which has demonstrated that increases in theta power reflect distraction during driving situations (Almahasneh et al., 2014; Savage et al., 2013). The fact that fontal theta was affected differently by cognitive load during the antisaccade task may be due to processes of reflexive orienting interfering with the processing of the secondary cognitive task, thus resulting in a decrease rather than an increase in theta power.

Fixation Event Related Potentials

It had previously been argued that decreases in overall occipital theta might be indicative of a reduction in depth of visual processing (Savage, Potter & Tater, 2013). In order to further examine this interpretation, we examined the effect of cognitive load on participant's fERPs in Experiments I & IV.

In the prosaccade task when cognitive load was high, the amplitude of fERPS was higher at central parietal sites. As central parietal sites are involved in vision for action system (Milner & Goodale, 2004) it could be reasoned that distraction resulted in more effort being required to translate visual information into an appropriate motor response.

In the antisaccade task the introduction of secondary cognitive load resulted in an increase in frontal processing negativity. As prolonged negativity has been associated with an increased processing in the respective area of the cortex (e.g., George et al., 1996) this result suggests that distraction resulted in increased processing at sites associated with executive functions such as task monitoring, error monitoring and inhibitory control. Considering the specific demands of the antisaccade task were to inhibit the prepotent eye movement towards a sudden onset target in favour of programming a volitional saccade in the opposite direction, it is perhaps not surprising that increasing secondary cognitive task demand resulted in more processing in areas associated with executive functions.

Interestingly in Experiment IV we found the opposite pattern for the effect of cognitive load on frontal processing negativity following fixation onsets. In this final study we found that when allowed to move their eyes freely across a video, participants' frontal processing negativity was significantly less negative when cognitive load was high. It could be speculated that the specific demands of the primary task between antisaccade and hazard perception tasks were affecting the direction of *f*ERPs. In the antisaccade task participants were required to make very structured eye movements, which were always roughly the same size, speed and purpose (don't move towards the target but always move away). The increase in processing negativity observed in the antisaccade task may be due to processes of inhibitory control related to the suppression of the reflexive prosaccade as well as cognitive task demand associated with computing the secondary task. In contrast to this when subjects were allowed to move their eyes freely (Experiment IV), we observed a significant reduction in amplitudes of *f*ERPs at occipital and less processing negativity at frontal sites. As previously argued, reduced amplitudes of *f*ERPs at occipital sites may be indicative of a reduced depth of visual processing within each fixation. We argue that the reduction in processing negativity at frontal sites of the cortex when cognitive load was high might indicate that areas associated with executive function were less active following fixation onsets. When cognitive load was high, overall increases in theta and decreases in alpha and beta frequency band power indicated that participants were processing the secondary task throughout the 30 seconds of the hazard perception clip. Reduced processing negativity following fixations may therefore indicate that executive functions, which were allocated to computing the secondary task, were not available to process the incoming visual information to the same extent as when full cognitive capacities were available. This was also demonstrated by the reduction of the *f*ERP signal size at occipital sites during this same time window.

We argue that in the pro and antisaccade tasks subjects were not required to process visual information to the same extent as when watching a hazard perception clip. Specifically pro- and antisaccade tasks rely on the processing of peripheral information, whereas viewing movie based hazard perception clips requires the processing of fixated items. In the antisaccade task each correct antisaccade is associated with executive functions such as inhibitory control (e.g., Hutton, 2008), which may not necessarily be present during each fixation when normally moving our eyes. Increased processing negativity following fixations in the antisaccade task were most likely due to the isolation of processes relating to inhibitory control with the addition of processing demands associated with computing the secondary task. Reduced frontal processing negativity and smaller *f*ERP signal size at occipital sites when distracted in the hazard perception task most likely indicated that subjects were freeing up resources engaged by the primary- in order to process the secondary task. Taken together results from this current thesis have shown that *f*ERPs are sensitive to subtle differences in the effects of distraction across different tasks.

Event Related Potentials

ERPs following motor responses were recorded in Experiments I and IV however the time window for which the differences between high and low load conditions were calculated was not the same for both tasks. This was most likely due to the structure of the pro- and antisaccade tasks. Directly after participants had pressed a button, the trial ended and the display changed thus influencing our EEG recordings. In the hazard perception task, the button press response did not lead to any visual feedback. Therefore in Experiment I differences between high and low load conditions were calculated around the time of the motor response (30 ms prior and 60 ms following) whereas in Experiment IV differences were calculated 200-400 ms following correct button responses.

When subjects were distracted in the prosaccade task, the average signal size of ERPs was significantly less positive going at central parietal and occipital parietal sites around the time of correct button presses. As the posterior parietal cortex (PPC) has been associated with “vision for action” systems (Milner & Goodale, 1995, 2004) it could be argued that the transformation of visual information into motor commands was less efficient when secondary cognitive task demand was high, which was also supported by a significant increase in VTs. In the antisaccade task, button press ERPs were more positive when cognitive load was high. As the frontal lobes as well as the DLFPC play an integral role in executive functions such as inhibitory control, working memory and task switching (Corbetta et al., 2008), this may be indicative of increases in computational and storage demands required to process both tasks simultaneously. Furthermore, behavioural results indicated that preoccupation with solving a puzzle did not result in a decrease in overall button press response performance in the antisaccade task. It could therefore be speculated that the increase in processing within areas associated with executive functions may be involved in maintaining primary task performance.

Although calculated for different time windows, certain spatial similarities were observed for the effects of load on participants button press ERPs between Experiments IV and I. Following correct responses in Experiment IV, high secondary cognitive task demand corresponded with significantly less negatively fluctuating ERPs at frontal and dorsolateral prefrontal (DLPFC) sites and significantly more negatively fluctuating ERPs at parietal and occipital sites.

Previous research has demonstrated a negative deflection shortly after erroneous responses (e.g., Falkenstein et al., 1991; Gehring et al., 1993), which has been termed error-related negativity (ERN) and is thought to act as an action monitoring function (e.g., Luu, Flaish & Tucher, 2000). However more recently studies have shown similar ERN activity following correct responses (correct response negativity - CRN). Therefore it was proposed that ERN/CRN activity were associated with response comparison processes (Vidal et al., 2000) or emotional responses to the reaction (Luu et al., 2000) rather than processes relating to error monitoring. It has been shown that amplitudes of CRNs are greater in high conflict trials when subjects were uncertain about their responses (Botvinick et al., 1999; Carter et al., 2000) indicating an involvement in error monitoring and response conflict resolution. Therefore we argue that an increase in CRN amplitudes following correct responses in the high cognitive load condition may suggest that subjects were less certain about their responses. This was most likely due to the fact that for the same time window processing at DLPF sites was significantly reduced.

Increased usages of executive functions are associated with increased processing negativity in the DLPFC (George et al., 1996). Results from Experiment IV indicated that amplitudes of CRN following correct button presses were significantly less negative in the high compared to the low secondary cognitive task demand condition. The reduction in processing negativity at DLPFC sites 200-400 ms after correct responses may therefore be an indication of a reduction in processing in areas associated with executive functions. Together results from Experiment I and IV demonstrated that secondary cognitive task demand resulted in a reduction in the efficiency of translating visual information into motor commands that processes of conflict monitoring were less active and that participants demonstrated less certainty about their responses.

A summary of the effects of cognitive load on oculomotor and behavioural measures across Experiments I (Pro /Antisaccade), II (Visual Search), IV (Hazard Perception 30-seconds) as well as Savage, Potter & Tatler's (2013) original (1-minute) Hazard Perception task can be seen in Table 1. The effect of cognitive load on tonic and phasic frequency outputs for both Experiment I (Pro/Antisaccade task) and Experiment IV (Hazard Perception task) can be seen in Table 2. ERPs around button responses as well as following fixation onsets (*f*ERPs) can be seen for Experiment I and II in Table 3.

Table 1, *Summary of the effects of cognitive load on Reaction Times (RT), Verification Times (VT), False Responses (FR), Time to Hit (TTH), Spread of fixations along X and Y axes, Number of Fixations (NFix), Number of Refixations (N Re-fix), Fixation Durations (Fix Dur), Saccade amplitudes (Sacc Amp), Saccade durations (Sacc Dur), First Saccade Peak Velocities (FSPV), Overall Saccade Peak Velovities (SPV), First Saccade Latencies (FSL), Blink Rates and Blink durations (Blink Dur) across all three experiments of this current thesis: Pro- and Antisaccade tasks, Target present and absent trials within structured and unstructured visual search, 30-second; as well as from Savage et al. (2013) original (1-Minute) hazard perception study.*

<table>
<tr><th></th><th colspan="3">Pro / Antisaccade</th><th colspan="5">Visual Search</th><th colspan="2">Hazard Perception</th></tr>
<tr><th></th><th></th><th></th><th></th><th colspan="2">Structured</th><th></th><th colspan="2">Unstructured</th><th></th><th></th></tr>
<tr><th></th><th>Pro</th><th></th><th>Anti</th><th>Pres.</th><th>Abs.</th><th></th><th>Pres.</th><th>Abs.</th><th>30-Second</th><th>1-Minute</th></tr>
<tr><td>Measure</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>RT</td><td>↑^{ii}</td><td>×</td><td>↑^{i}</td><td>↑</td><td>↑</td><td></td><td>↑</td><td>↑</td><td>-</td><td>↑</td></tr>
<tr><td>VT</td><td>↑^{ii}</td><td>×</td><td>↑^{i}</td><td>↑^{i}</td><td>NA</td><td></td><td>↑^{ii}</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>FR</td><td>-</td><td></td><td>-</td><td>-^{i}</td><td>↑</td><td></td><td>-^{ii}</td><td>↑</td><td>-</td><td>↑</td></tr>
<tr><td>TTH</td><td>↑</td><td></td><td>↑</td><td>↑</td><td>NA</td><td></td><td>↑</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>X-Spread</td><td>↓</td><td></td><td>↓</td><td>-</td><td>↓</td><td></td><td>-</td><td>↓</td><td>↓</td><td>↓</td></tr>
<tr><td>Y-Spread</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>N Fix</td><td>NA</td><td></td><td>NA</td><td>↑^{i}</td><td>↑</td><td></td><td>↑^{ii}</td><td>↑</td><td>-</td><td>NA</td></tr>
<tr><td>N Re-fix</td><td>NA</td><td></td><td>NA</td><td>↑^{i}</td><td>↑</td><td></td><td>↑^{ii}</td><td>↑</td><td>-</td><td>NA</td></tr>
<tr><td>Fix Dur</td><td>-</td><td></td><td>-</td><td>↑</td><td>↑</td><td></td><td>↑</td><td>↑</td><td>-</td><td>-</td></tr>
<tr><td>Sacc Amp</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Sacc Dur</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td></td><td>-</td><td>-</td><td>↑</td><td>-</td></tr>
<tr><td>FSPV</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td>NA</td></tr>
<tr><td>SPV</td><td>NA</td><td></td><td>NA</td><td>-</td><td>↓</td><td></td><td>-</td><td>↓</td><td>↑</td><td>↑</td></tr>
<tr><td>FSL</td><td>↑</td><td></td><td>↑</td><td>↑</td><td>↑</td><td></td><td>↑</td><td>↑</td><td>↑</td><td>NA</td></tr>
<tr><td>Blink Rate</td><td>-</td><td></td><td>-</td><td colspan="2">↑^{ii}</td><td>×</td><td colspan="2">↑^{i}</td><td>↑</td><td>↑</td></tr>
<tr><td>Blink Dur</td><td>-^{i}</td><td>×</td><td>-^{ii}</td><td>-</td><td>-</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Legend:
↑ Indicates increase in high cognitive load condition
↓ Indicates decrease in high cognitive load condition
- Indicates no difference between high and low load conditions
i / ii Indicates effect size if difference was significant (i – smaller / ii – larger)
× Indicates interaction between the primary task maniplations and cognitive load

Table 2, *Summary of the effect of secondary cognitive task demand on overall (tonic) Alpha, Beta and Theta frequency band outputs as well as target onset (TO – phasic) Alpha, Beta and Theta frequency power at Frontal, Central, Parietal, Temporal and Occipital sites for Pro – and Antisaccade tasks as well as the current 30-Second and original 1-Minute Hazard Perception tasks.*

		Pro / Antisaccade		**Hazard Perception**	
		Pro	**Anti**	**30 Second**	**1 Minute**
Measure					
Alpha	*Frontal*	↓	-	-	NA
	Central	↓	-	↓	NA
	Parietal	↓	↓	-	NA
	Temporal	-	-	-	NA
	Occipital	↓	-	-	NA
Beta	*Frontal*	↓	-	↓	NA
	Central	↓	-	-	NA
	Parietal	↓	-	-	NA
	Temporal	-	-	-	NA
	Occipital	↓	-	-	NA
Theta	*Frontal*	↓	-	-	↑
	Central	-	-	↑	-
	Parietal	-	-	↑	-
	Temporal	-	-	↑	-
	Occipital	-	-	-	↓
TO Alpha	*Frontal*	-	-	-	NA
	Central	-	-	↑	NA
	Parietal	-	-	↑	NA
	Temporal	-	-	-	NA
	Occipital	-	-	↑	NA
TO Beta	*Frontal*	-	-	-	NA
	Central	-	-	-	NA
	Parietal	-	-	↑	NA
	Temporal	-	-	-	NA
	Occipital	-	-	↑	NA
TO Theta	*Frontal*	-	-	↑	NA
	Central	-	-	↑	NA
	Parietal	-	-	↑	NA
	Temporal	-	-	-	NA
	Occipital	-	-	-	NA

Legend:
↑ Indicates increase in high cognitive load condition
↓ Indicates decrease in high cognitive load condition
- Indicates no difference between high and low load conditions

Table 3, *Summary of the effect of secondary cognitive task demand on fixation Event Related Potentials (fERPs) and Button Press Event Related Potentials (BP ERPs) at Frontal, Central, Parietal, Temporal and Occipital sites for Pro – and Antisaccade tasks as well as the current 30-Second Hazard Perception tasks.*

		Pro / Antisaccade		Hazard Perception
		Pro	**Anti**	**30 Second**
	Measure			
***f*ERPs**	*Frontal*	-	↓	↑
	Central	↑	-	-
	Parietal	↑	-	↓
	Temporal	-	-	↓
	Occipital	-	-	↓
BP ERPs	*Frontal*	-	↑	↑
	Central	↓	-	-
	Parietal	↓	-	↓
	Temporal	-	↑	-
	Occipital	-	-	↓

Legend:
↑ Indicates more positive going activity in high cognitive load condition
↓ Indicates more negative going activity in high cognitive load condition
- Indicates no difference between high and low load conditions

Oculomotor and Electrophysiological markers of distraction

The most reliable indicators of secondary cognitive task demand across both low-level and complex visual tasks were: 1) the reduction in the spread of fixations along the x-axis; 2) the increase in blink rates; 3) the increase in first saccade latencies; and 4) the reduction in overall alpha and beta frequency band output. As indicated in Tables 1, 2 and 3 of this current chapter, there were a variety of measures that were affected by secondary cognitive task demand within each individual experiment. However the metrics outlined above showed consistent effects across all experiments in which eye movements and EEG data were recorded.

Limitations and Future research

We have identified a set of oculomotor and electrophysiological markers of cognitive distraction that are robust over a series of different primary tasks. More research however is needed to model the value of these markers in terms of predicting distraction. Furthermore the effects and interaction of age and experience with secondary cognitive distraction is yet to be fully understood. None of the experiments in the current thesis manipulated the visual task demand of the primary task. Experiment IV indicated that events happening in the primary task influence the magnitude of previously identified markers of distraction. However more research is needed to tease apart the effects of primary and secondary task demands on participants' oculomotor and electrophysiological metrics.

Two issues that remain unclear are 1) the differences in eye movements between vision for perception and vision for action conditions and 2) whether distraction has a different effect when performing these two distinctly different tasks. The hazard perception task requires subjects to monitor situations for potential hazards whereas this is only a very small portion of what actually occurs during real driving; where vehicle control, lane and heading maintenance (to name only a few) also play a vital role.

It would be of great interest to determine the applicability of the observed markers of distraction in real-life driving tasks. The ultimate aim of this line of research is to identify distraction in real life situations. Laboratory experiments are a good way with which to identify potential markers of distraction however this does not guarantee that secondary cognitive task demand has the same effects on eye movements during real driving.

General Conclusions

The main findings of the individual experiments of the current thesis were as follow: 1) secondary cognitive task demand interfered with processes of orienting, inhibitory control (Experiment I) and visual search (Experiment II); 2) the working memory element of secondary cognitive tasks resulted in greater decrements in hazard perception performance compared to mechanisms relating to language processing and production (Experiment III); 3) the presented oculomotor and electrophysiological markers were sensitive to variations in cognitive load although primary hazard perception task performance was not affected and 4) the susceptibility of these markers was affected by the hazard presence (Experiment IV).

By breaking down the hazard perception task into some of its individual component processes we were able to make more robust claims as to the cause of increases in RTs observed in hazard perception tasks when people were distracted. Results from this current thesis have demonstrated that secondary cognitive task demand interferes with processes relating to 1) alerting to the onset of the primary task (longer first saccade latencies); 2) search during the primary task (longer fixation durations, more fixations and re-fixations as well as a reduced spread of fixations); and 3) verifying potential targets as hazards once search has terminated (longer VTs). Furthermore we have shown that cognitive load negatively affects mechanisms of reflexive orienting (higher first saccade error rates in the prosaccade task) and inhibitory control (higher first saccade error rates in the antisaccade task).
Across both experiments in which EEG data was recorded we have demonstrated that distraction by a secondary cognitive task resulted in changes to alpha beta and theta frequency power. However the most reliable overall indicator of load was a decrease in tonic alpha frequency power, which was observed in both pro- and antisaccade as well as hazard perception paradigms.

The current thesis has demonstrated that analyses of *f*ERPs and ERPs may be a viable method with which to study the effects of cognitive load on visual processing as well as mechanisms relating to response selection and error monitoring. Furthermore we have shown that this approach is possible in low level as well as complex visual tasks in which participants were able to move their eyes freely.

There are different avenues of research that could develop from the current thesis. First on a theoretical basis it would be of interest to mathematically model the effects of cognitive load on the basic elements of eye movement behaviour in order to determine their predictive values. On a practical level this research could be applied to the development of distraction detection devices, which do not only detect but also alert subjects to their distracted states. This would be of vital importance not only within the field of transportation but also safety and human factors research. Lastly, it would be of great interest to co-register EEG and eye movements in real-life driving situations. The comparison of the effects of cognitive load on hazard perception and real life driving would further our understanding on the effects of distraction during driving. Finally comparing and contrasting eye movements between hazard perception and real life driving tasks may reveal differences in processes relating to vision for perception and vision for action.

References

Abrams, R. A., Meyer, D. E., & Kornblum, S. (1989). Speed and accuracy of saccadic eye movements: characteristics of impulse variability in the oculomotor system. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 529.

Ahopalo, P., Lehikoinen, A., Summala, H., (1987). Experience and Response Latencies in Hazard Perception (in Finnish). University of Helsinki, Traffic Research Unit, Helsinki.

Allen, J. J., Iacono, W. G., Depue, R. A., & Arbisi, P. (1993). Regional electroencephalographic asymmetries in bipolar seasonal affective disorder before and after exposure to bright light. *Biological Psychiatry*, *33*(8–9), 642–646.

Alm, H., & Nilsson, L. (1994). Changes in driver behaviour as a function of handsfree mobile phones— A simulator study. *Accident Analysis & Prevention*, *26*(4), 441–451.

Almahasneh, H., Chooi, W.-T., Kamel, N., & Malik, A. S. (2014). Transportation Research Part F. *Transportation Research Part F: Psychology and Behaviour*, *26*(PA), 218–226. doi:10.1016/j.trf.2014.08.001

Amador, N., Schlag-Rey, M., & Schlag, J. (1998). Primate antisaccades. I. Behavioral characteristics. *Journal of Neurophysiology*, *80*(4), 1775-1786.

Andersen, R. A. (1997). Neural mechanisms of visual motion perception in primates. *Neuron*, *18*(6), 865-872.

Anstey, K., Wood, J., Lords, S., & Walker, J. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical Psychology Review*, *25*(1), 45–65. doi:10.1016/j.cpr.2004.07.008.

Antin, J. A., Dingus, T. A., Hulse, M. C., & Wierwille, W. W. (1990). An evaluation of the effectiveness and efficiency of an automobile moving-map navigational display. *International Journal of Man–Machine Studies, 33*, 581–594.

App, E., & Debus, G. (1998). Saccadic velocity and activation: development of a diagnostic tool for assessing energy regulation. *Ergonomics*, *41*(5), 689–697. doi:10.1080/001401398186856

Ashcraft, M. H., Yamashita, T. S., & Aram, D. M. (1992). Mathematics performance in left and right brain-lesioned children and adolescents. *Brain and Cognition*, *19*(2), 208-252.

Baccino, T., & Manunta, Y. (2005). Eye-Fixation-Related Potentials: Insight into Parafoveal Processing. *Journal of Psychophysiology*, *19*(3), 204–215. doi:10.1027/0269-8803.19.3.204

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in cognitive sciences*, *4*(11), 417-423.

Baddeley, A. D. (1997). *Human memory: Theory and practice*. Psychology Press.

Baddeley, A. D., & Hitch, G. (1974). Working memory. *Psychology of learning and motivation*, *8*, 47-89.

Baddeley, A., Logie, R., Nimmo-Smith, I., & Brereton, N. (1985). Components of fluent reading. *Journal of memory and language*, *24*(1), 119-131.

Bahill, A. T., Clark, M. R., & Stark, L. (1975). The main sequence, a tool for studying human eye movements. *Mathematical Biosciences*, *24*(3), 191-204.

Baldwin, C. L., & Coyne, J. T. (2003). Mental workload as a function of traffic density: Comparison of physiological, behavioral, and subjective indices. In *Proceedings of the Second International Driving Symposium on Human Factors* -19-24.

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and language*, *68*(3), 255-278.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H. & Rcpp, L. (2014). Package 'lme4'. *R Foundation for Statistical Computing, Vienna*.

Bates, J. A. V. (1951). Electrical activity of the cortex accompanying movement. *The Journal of physiology*, *113*(2-3), 240-257.

Beck, M. R., Lohrenz, M. C., & Trafton, J. G. (2010). Measuring search efficiency in complex visual search tasks: global and local clutter. *Journal of experimental psychology: applied*, *16*(3), 238.

Becker, W. (1989). The neurobiology of saccadic eye movements. Metrics. *Reviews of oculomotor research*, *3*, 13.

Bell, A. H., Everling, S., & Munoz, D. (2000). Influence of stimulus eccentricity and direction on characteristics of pro-and antisaccades in non-human primates. *Journal of Neurophysiology*, *84*(5), 2595-2604.

Benedetto, S., Pedrotti, M., Minin, L., Baccino, T., Re, A., & Montanari, R. (2011). Driver workload and eye blink duration. *Transportation research part F: traffic psychology and behaviour*, *14*(3), 199-208.

Bergasa, L. M., Nuevo, J., Sotelo, M. A., Barea, R., & Lopez, M. E. (2006). Real-time system for monitoring driver vigilance. *Intelligent Transportation Systems, IEEE Transactions on*, *7*(1), 63-77.

Boer, E. R. (2000). Behavioral entropy as an index of workload. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* 44 (17), 125-128.

Botvinick, M., Nystrom, L. E., Fissell, K., Carter, C. S., & Cohen, J. D. (1999). Conflict monitoring versus selection-for-action in anterior cingulate cortex. *Nature*, *402* (6758), 179-181.

Bowditch, S. C. (2001). Driver distraction: A replication and extension of Brown, Tickner & Simmons (1969). In: G. B. Grayson (Ed.), Behavioural research in road safety 11. Crowthorne: Transport Research Laboratory.

Brannon, E. M., Cabeza, R., Huettel, S. A., LaBar, K. S., Platt, M. L., & Woldorff, M. G. (2008). Principles of cognitive neuroscience. *83(3), 757*. Sunderland, MA: Sinauer Associates.

Bresnahan, S. M., Anderson, J. W., & Barry, R. J. (1999). Age-related changes in quantitative EEG in attention-deficit/hyperactivity disorder. *Biological psychiatry*, *46*(12), 1690-1697.

Brickett, P. A., Weinberg, H., & Davis, C. M. (1984). Cerebral potentials preceding visually triggered saccades. *Annals of the New York Academy of Sciences*, *425*(1), 429-433.

Briem, V., & Hedman, L. R. (1995). Behavioural effects of mobile telephone use during simulated driving. *Ergonomics*, *38*(12), 2536-2562.

Brookhuis, K. A., & de Waard, D. (2010). Monitoring drivers' mental workload in driving simulators using physiological measures. *Accident Analysis & Prevention*, *42*(3), 898-903.

Brookhuis, K. A., de Vries, G., & de Waard, D. (1991). The effects of mobile telephoning on driving performance. *Accident Analysis & Prevention*, *23*(4), 309-316.

Bundesen, C. (1990). A theory of visual attention. *Psychological review*, *97*(4), 523.

Buswell, G. T. (1935). *How people look at pictures,* 136-141. Chicago: University of Chicago Press.

Cant, B. R., & Bickford, R. G. (1967). The effect of motivation on the contingent negative variation (CNV). *Electroencephalography and clinical neurophysiology*, *23*(6), 594.

Carpenter, R., & Williams, M. (1995). Neural computation of log likelihood in control of saccadic eye movements. *Nature*, *377*(6544), 59–62.

Carter, C. S., Macdonald, A. M., Botvinick, M., Ross, L. L., Stenger, V. A., Noll, D., & Cohen, J. D. (2000). Parsing executive processes: strategic vs. evaluative functions of the anterior cingulate cortex. *Proceedings of the National Academy of Sciences*, *97*(4), 1944-1948.

Chapman, P. R., & Underwood, G. (1998). Visual search of driving situations: Danger and experience. *Perception-London-*, *27*, 951-964.

Chun, M. M., & Wolfe, J. M. (1996). Just say no: How are visual searches terminated when there is no target present? *Cognitive Psychology*, *30*(1), 39–78.

Clementz, B. A., Sponheim, S. R., Iacono, W. G., & Beiser, M. (1994). Resting EEG in first-episode schizophrenia patients, bipolar psychosis patients, and their first-degree relatives. *Psychophysiology*, *31*(5), 486-494.

Colby, C. L., & Goldberg, M. E. (1999). Space and attention in parietal cortex. *Annual review of neuroscience*, *22*(1), 319-349.

Coles, M. G., Smid, H. G., Scheffers, M. K., & Otten, L. J. (1995). Mental chronometry and the study of human information processing.

Conway, M. A., & Bekerian, D. A. (1987). Organization in autobiographical memory. *Memory & Cognition*, *15*(2), 119-132.

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron*, *58*(3), 306-324.

Cowan, N. (1995). Sensory memory and its role in information processing. *Electroencephalography and clinical neurophysiology. Supplement*, *44*, 21.

Cowley, J. A. (2013). Towards a Theory of Mind Wandering in Relation to Task Type, Behavioral Responses, and Respective Adverse Consequences During the Operation of Manned Vehicles – *PhD Dissertation, North Carolina State University.*

Crundall, D. E., & Underwood, G. (1998). Effects of experience and processing demands on visual information acquisition in drivers. *Ergonomics*, *41*(4), 448-458.

Crundall, D., Bains, M., Chapman, P., & Underwood, G. (2005). Regulating conversation during driving: a problem for mobile telephones? *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(3), 197-211.

Curry, G. A., Wilde, G. J. S., Hieatt, D. J., Road, C., & Branch, M. V. T. S. (1975). *Task Load in the Motor Vehicle Operator: a Comparative Study of Assessment Procedures*. Road and Motor Vehicle Traffic Safety Branch, Ministry of Transport, Canada.

De Waard, D., & Brookhuis, K. A. (1991). Assessing driver status: a demonstration experiment on the road. *Accident analysis & prevention*, *23*(4), 297-307.

Deery, H. A., & Fildes, B. N. (1999). Young novice driver subtypes: Relationship to high-risk behavior, traffic accident record, and simulator driving performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *41*(4), 628-643.

Deiber, M. P., Missonnier, P., Bertrand, O., Gold, G., Fazio-Costa, L., Ibanez, V., & Giannakopoulos, P. (2007). Distinction between perceptual and attentional processing in working memory tasks: a study of phase-locked and induced oscillatory brain dynamics. *Journal of cognitive neuroscience*, *19*(1), 158-172.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual review of neuroscience*, *18*(1), 193-222.

Di Stasi, L. L., Contreras, D., Cándido, A., Cañas, J. J., & Catena, A. (2011). Behavioral and eye-movement measures to track improvements in driving skills of vulnerable road users: First-time motorcycle riders. *Transportation research part F: traffic psychology and behaviour*, *14*(1), 26-35.

Di Stasi, L. L., Renner, R., Catena, A., Cañas, J. J., Velichkovsky, B. M., & Pannasch, S. (2012). Towards a driver fatigue test based on the saccadic main sequence: A partial validation by subjective report data. *Transportation research part C: emerging technologies*, *21*(1), 122-133.

Di Stasi, L. L., Renner, R., Staehr, P., Helmert, J. R., Velichkovsky, B. M., Cañas, J. J., & Pannasch, S. (2010). Saccadic peak velocity sensitivity to variations in mental workload. *Aviation, space, and environmental medicine*, *81*(4), 413-417.

Dias, E. C., & Segraves, M. A. (1999). Muscimol-induced inactivation of monkey frontal eye field: effects on visually and memory-guided saccades. *Journal of Neurophysiology*, *81*(5), 2191-2214.

Diefendorf, A. R., & Dodge, R. (1908). An experimental study of the ocular reactions of the insane from photographic records. *Brain*, *31*(3), 451-489.

Dingus, T., McGehee, D., HULSE, M., Jahns, S., Manakkal, N., Mollenhauer, M., & Fleischman, R. (1995). *TRAVTEK Evaluation Task C SUB 3-Camera Car Study. Final Report* (No. FHWA-RD-94-076).

Dodge, R. (1917). The laws of relative fatigue. *Psychological Review*, *24*(2), 89.

Dodge, R., & Cline, T. S. (1901). The angle velocity of eye movements. *Psychological Review*, *8*(2), 145.

Droll, J. A., Hayhoe, M. M., Triesch, J., & Sullivan, B. T. (2005). Task demands control acquisition and storage of visual information. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(6), 1416.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological review*, *96*(3), 433.

Earle, J. B. (1988). Task difficulty and EEG alpha asymmetry: an amplitude and frequency analysis. *Neuropsychobiology*, *20*(2), 96-112.

Edelman, J. A., & Goldberg, M. E. (2001). Dependence of saccade-related activity in the primate superior colliculus on visual target presence. *Journal of Neurophysiology*, *86*(2), 676-691.

Edelman, J. A., Valenzuela, N., & Barton, J. J. (2006). Antisaccade velocity, but not latency, results from a lack of saccade visual guidance. *Vision research*, *46*(8), 1411-1421.

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(2), 97-120.

Ettinger, U., Antonova, E., Crawford, T. J., Mitterschiffthaler, M. T., Goswani, S., Sharma, T., & Kumari, V. (2005). Structural neural correlates of prosaccade and antisaccade eye movements in healthy humans. *NeuroImage*, *24*(2), 487–494. doi:10.1016/j.neuroimage.2004.08.019

Evans, L. (2004). Handbook of Driving Simulation for Engineering, Medicine and Psychology. Traffic Safety. Bloomfield Hills, Michigan: Science Serving Society. ISBN 0-9754871-0-8.

Evdokimidis, I., Constantinidis, T. S., Liakopoulos, D., & Papageorgiou, C. (1996). The increased reaction time of antisaccades. What makes the difference? *International journal of psychophysiology*, *22*(1), 61-65.

Evdokimidis, I., Smyrnis, N., Constantinidis, T., Stefanis, N., Avramopoulos, D., Paximadis, C., & Stefanis, C. (2002). The antisaccade task in a sample of 2,006 young men. *Experimental Brain Research*, *147*(1), 45-52.

Everling, S., & Fischer, B. (1998). The antisaccade: a review of basic research and clinical studies. *Neuropsychologia*, *36*(9), 885-899.

Everling, S., Dorris, M. C., Klein, R. M., & Munoz, D. P. (1999). Role of primate superior colliculus in preparation and execution of anti-saccades and pro-saccades. *The Journal of neuroscience*, *19*(7), 2740-2754.

Everling, S., Krappmann, P., & Flohr, H. (1997). Cortical potentials preceding pro- and antisaccades in man. *Electroencephalography and clinical neurophysiology*, *102*(4), 356-362.

Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and clinical neurophysiology*, *78*(6), 447-455.

Ferraina, S., Paré, M., & Wurtz, R. H. (2002). Comparison of cortico-cortical and cortico-collicular signals for the generation of saccadic eye movements. *Journal of Neurophysiology*, *87*(2), 845-858.

Findlay, J. M. (1997). Saccade target selection during visual search. *Vision research*, *37*(5), 617-631.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, *22*(04), 661-674.

Fischer, B., & Breitmeyer, B. (1987). Mechanisms of visual attention revealed by saccadic eye movements. *Neuropsychologia*, *25*(1), 73-83.

Fischer, B., & Weber, H. (1992). Characteristics of “anti” saccades in man. *Experimental Brain Research*, *89*(2), 415-424.

Fischer, B., & Weber, H. (1993). Express saccades and visual attention. *Behavioral and Brain Sciences*, *16*(03), 553-567.

Fisk, A. D., & Hodge, K. A. (1992). Retention of trained performance in consistent mapping search after extended delay. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *34*(2), 147-164.

Fleck, M. S., & Mitroff, S. R. (2007). Rare targets are rarely missed in correctable search. *Psychological Science*, *18*(11), 943-947.

Fogarty, C., & Stern, J. A. (1989). Eye movements and blinks: their relationship to higher cognitive processes. *International Journal of Psychophysiology*, *8*(1), 35-42.

Fogassi, L., & Luppino, G. (2005). Motor functions of the parietal lobe. *Current opinion in neurobiology*, *15*(6), 626-631.

Fukuda, K., Stern, J. A., Brown, T. B., & Russo, M. B. (2005). Cognition, blinks, eye-movements, and pupillary movements during performance of a running memory task. *Aviation, space, and environmental medicine*, *76*(1), 75-85.

Fukushima, J., Fukushima, K., Chiba, T., Tanaka, S., Yamashita, I., & Kato, M. (1988). Disturbances of voluntary control of saccadic eye movements in schizophrenic patients. *Biological psychiatry*, *23*(7), 670-677.

Fuster, J. M. (1988). *Prefrontal cortex* (pp. 107-109). Birkhäuser Boston.

Fuster, J. M. (1997). Network memory. *Trends in neurosciences*, *20*(10), 451-459.

Galán, F. C., & Beal, C. R. (2012). EEG estimates of engagement and cognitive workload predict math problem solving outcomes. In *User Modeling, Adaptation, and Personalization*, 51-62. Springer Berlin Heidelberg.

Galley, N. (1993). The evaluation of the electrooculogram as a psychophysiological measuring instrument in the driver study of driver behaviour. *Ergonomics*, *36*(9), 1063-1070.

Gattaz, W. F., Mayer, S., Ziegler, P., Platz, M., & Gasser, T. (1992). Hypofrontality on topographic EEG in schizophrenia. *European archives of psychiatry and clinical neuroscience*, *241*(6), 328-332.

Gaymard, B., Ploner, C. J., Rivaud-Pechoux, S., & Pierrot-Deseilligny, C. (1999). The frontal eye field is involved in spatial short-term memory but not in reflexive saccade inhibition. *Experimental Brain Research*, *129*(2), 288-301.

Gehring, W. J., Goss, B., Coles, M. G., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological science*, *4*(6), 385-390.

George, N., Evans, J., Fiori, N., Davidoff, J., & Renault, B. (1996). Brain events related to normal and moderately scrambled faces. *Cognitive Brain Research*, *4*(2), 65-76.

Gerhardstein, P., & Rovee-Collier, C. (2002). The development of visual search in infants and very young children. *Journal of Experimental Child Psychology*, *81*(2), 194-215.

Gevins, A., & Cutillo, B. (1993). Spatiotemporal dynamics of component processes in human working memory. *Electroencephalography and clinical neurophysiology*, *87*(3), 128-143.

Gevins, A., Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice. *Cerebral cortex*, *7*(4), 374-385.

Gilchrist, I. D., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology*, *10*(19), 1209-1212.

Gilchrist, I. D., & Harvey, M. (2006). Evidence for a systematic component within scan paths in visual search. *Visual Cognition*, *14*(4-8), 704-715.

Gilden, L., Vaughan, H. G., & Costa, L. D. (1966). Summated human EEG potentials with voluntary movement. *Electroencephalography and clinical Neurophysiology*, *20*(5), 433-438.

Godden, D. R., & Baddeley, A. D. (1975). Context-dependent memory in two natural environments: On land and underwater. *British Journal of psychology*, *66*(3), 325-331.

Godijn, R., & Kramer, A. F. (2008). Oculomotor capture by surprising onsets. *Visual Cognition*, *16*(2-3), 279-289.

Godthelp, H., Milgram, P., & Blaauw, G. J. (1984). The development of a time-related measure to describe driving strategy. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *26*(3), 257-268.

Grace, P. M., Stanford, T., Gentgall, M., & Rolan, P. E. (2010). Utility of saccadic eye movement analysis as an objective biomarker to detect the sedative interaction between opioids and sleep deprivation in opioid-naive and opioid-tolerant populations. *Journal of Psychopharmacology*, *24*(11), 1631-1640.

Green, D. M. & Swets, J. A. (1966). Signal Detection Theory and Psychophysics. Wiley, New York.

Greenberg, J., Artz, B., & Cathey, L. (2003). The effect of lateral motion cues during simulated driving. *Proceedings of DSC North America*.

Guitton, D., Buchtel, H. A., & Douglas, R. M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research*, *58*(3), 455-472.

Gur, D., Bandos, A. I., Fuhrman, C. R., Klym, A. H., King, J. L., & Rockette, H. E. (2007). The prevalence effect in a laboratory environment: Changing the confidence ratings. *Academic Radiology, 14*, 49–53.

Gur, D., Rockette, H. E., Armfield, D. R., Blachar, A., Bogan, J. K., Brancatelli, G. (2003). Prevalence effect in a laboratory environment. *Radiology, 228*, 10–14.

Haigney, D. (1995). Compensation-implications for road safety. *InRoads*, *17*(1).

Haigney, D. E., Taylor, R. G., & Westerman, S. J. (2000). Concurrent mobile (cellular) phone use and driving performance: task demand characteristics and compensatory processes. *Transportation Research Part F: Traffic Psychology and Behaviour*, *3*(3), 113-121.

Haigney, D., & Taylor, R. (1998). Free Road Safety Resource provided by Royal Society for the Prevention of Accidents.

Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision research*, *18*(10), 1279-1296.

Halligan, P. W., & Marshall, J. C. (1994). Toward a principled explanation of unilateral neglect. *Cognitive Neuropsychology*, *11*(2), 167-206.

Hancock, P. A., Lesch, M., & Simmons, L. (2003). The distraction effects of phone use during a crucial driving maneuver. *Accident Analysis & Prevention*, *35*(4), 501-514.

Harbluk, J. L., Noy, Y. I., & Eizenman, M. (2002). The impact of cognitive distraction on driver visual behaviour and vehicle control. *Transports Canada* (No. TP# 13889 E).

Harmon-Jones, E., & Allen, J. J. (1997). Behavioral activation sensitivity and resting frontal EEG asymmetry: covariation of putative indicators related to risk for mood disorders. *Journal of abnormal psychology*, *106*(1), 159.

Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B. (2003). Visual memory and motor planning in a natural task. *Journal of vision*, *3*(1), 6.

Hayhoe, M., & Ballard, D. (2005). Eye movements in natural behavior. *Trends in cognitive sciences*, *9*(4), 188-194.

Henderson, J. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences*, *7*(11), 498–504. doi:10.1016/j.tics.2003.09.006

Henderson, J. M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. *Eye guidance in reading and scene perception*, *11*, 269-293.

Henriksson, N. G., Pyykko, I., Schalen, L., & Wennmo, C. (1980). Velocity patterns of rapid eye movements. *Acta oto-laryngologica*, *89*(3-6), 504-512.

Hooge, I. T. C., & Erkelens, C. J. (1999). Peripheral vision and oculomotor control during visual search. *Vision research*, *39*(8), 1567-1575.

Hoppe, M., Wennberg, R., Tai, P., & Pohlmann-Eden, B. (2009). EEG in epilepsy. *Textbook of Stereotactic and Functional Neurosurgery*, 2575-2585.

Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature*, *394*(6693), 575-577.

Horrey, W. J., & Wickens, C. D. (2004). Driving and side task performance: The effects of display clutter, separation, and modality. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *46*(4), 611-624.

Horswill, Mark S. and McKenna, Frank P. (2004). Drivers' hazard perception ability: Situation awareness on the road. In Simon Banbury and Sebastien Tremblay (Ed.), *A cognitive approach to situation awareness: Theory and application* 1st ed. (pp. 155-175) UK: Ashgate Publishing, Ltd.

Hosking, S. G., Young, K., & Regan, M. A. (2005). The effects of text messaging on young novice driver performance. *Monash University, Accident Research Centre,* (Report No. 246).

Hutton, S. B. (2008). Cognitive control of saccadic eye movements. *Brain and cognition*, *68*(3), 327-340.

Hutton, S. B., & Ettinger, U. (2006). The antisaccade task as a research tool in psychopathology: a critical review. *Psychophysiology*, *43*(3), 302-313.

Irwin, D. A., Knott, J. R., McAdam, D. W., & Rebert, C. S. (1966). Motivational determinants of the “contingent negative variation”. *Electroencephalography and Clinical Neurophysiology*, *21*(6), 538-543.

Irwin, M., Fitzgerald, C., & Berg, W. P. (2000). Effect of the intensity of wireless telephone conversations on reaction time in a braking response. *Perceptual and motor skills*, *90*(3c), 1130-1134.

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision research*, *40*(10), 1489-1506.

Jacobson, P. D., & Gostin, L. O. (2010). Reducing distracted driving: regulation and education to avert traffic injuries and fatalities. *JAMA*, *303*(14), 1419-1420.

James, W. (1890). The principles of psychology. (Vol. 1). *New York: Holt*.

Janssen, W. H., & Gaillard, A. W. (1984). Task load and stress on the road: Preliminaries to a model of route choice. *Transportation Research Board,* (Report No. 1984-C-10 Monograph).

Jensen, O., & Tesche, C. D. (2002). Frontal theta activity in humans increases with memory load in a working memory task. European Journal of Neuroscience, 15, 1395–1399.

Johnston, K., & Everling, S. (2008). Neurophysiology and neuroanatomy of reflexive and voluntary saccades in non-human primates. *Brain and cognition*, *68*(3), 271-283.

Just, M. A., & Carpenter, P. A. (1979). Eye fixations and cognitive processes. *Cognitive Psychology*, *8*(4), 441–480.

Just, M. A., Keller, T. A., & Cynkar, J. (2008). A decrease in brain activation associated with driving when listening to someone speak. *Brain Research*, *1205*, 70–80. doi:10.1016/j.brainres.2007.12.075

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive psychology*, *24*(2), 175-219.

Kass, S. J., Cole, K. S., & Stanny, C. J. (2007). Effects of distraction and experience on situation awareness and simulated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *10*(4), 321-329.

Kayser, J., & Tenke, C. E. (2003). Optimizing PCA methodology for ERP component identification and measurement: theoretical rationale and empirical evaluation. *Clinical neurophysiology*, *114*(12), 2307-2325.

Kazai, K., & Yagi, A. (2003). Comparison between the lambda response of eye-fixation-related potentials and the P100 component of pattern-reversal visual evoked potentials. *Cognitive, Affective, & Behavioral Neuroscience*, *3*(1), 46-56.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of experimental psychology*, *55*(4), 352.

Klauer, S. G. (2005). Assessing the Effects of Driving Inattention on Relative Crash Risk. *PhD Thesis, Virginia Tech.*

Kliegl, R., Dambacher, M., Dimigen, O., Jacobs, A. M., & Sommer, W. (2012). Eye movements and brain electric potentials during reading. *Psychological research*, *76*(2), 145-158.

Kliegl, R., Hohenstein, S., Yan, M., & McDonald, S. A. (2013). How preview space/time translates into preview cost/benefit for fixation durations during reading. *The Quarterly Journal of Experimental Psychology*, *66*(3), 581–600. doi:10.1080/17470218.2012.658073

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain research reviews*, *29*(2), 169-195.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in cognitive sciences*, *16*(12), 606-617.

Klimesch, W., Doppelmayr, M., Russegger, H., & Pachinger, T. (1996). Theta band power in the human scalp EEG and the encoding of new information. *Neuroreport*, *7*(7), 1235-1240.

Klimesch, W., Doppelmayr, M., Russegger, H., Pachinger, T., & Schwaiger, J. (1998). Induced alpha band power changes in the human EEG and attention. *Neuroscience letters*, *244*(2), 73-76.

Klimesch, W., Doppelmayr, M., Schimke, H., & Ripper, B. (1997). Theta synchronization and alpha desynchronization in a memory task. *Psychophysiology*, *34*(2), 169-176.

Klimesch, W., Doppelmayr, M., Schwaiger, J., Auinger, P., & Winkler, T. (1999). Paradoxical'alpha synchronization in a memory task. *Cognitive Brain Research*, *7*(4), 493-501.

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: the inhibition–timing hypothesis. *Brain research reviews*, *53*(1), 63-88.

Klimesch, W., Schimke, H., & Schwaiger, J. (1994). Episodic and semantic memory: an analysis in the EEG theta and alpha band. *Electroencephalography and clinical Neurophysiology*, *91*(6), 428-441.

Kolb, B., & Wishaw, I. Q. (1990). Fundamentals of Human Neuropsychology. Worth Publishers, New York.

Konstantopoulos, P., Chapman, P., & Crundall, D. (2010). Driver's visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers' eye movements in day, night and rain driving. *Accident Analysis & Prevention*, *42*(3), 827-834.

Kornhuber, H. H., & Deecke, L. (1965). Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotential und reafferente Potentiale. *Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere*, *284*(1), 1-17.

Kramer, A. F., Sirevaag, E. J., & Braune, R. (1987). A psychophysiological assessment of operator workload during simulated flight missions. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *29*(2), 145-160.

Lal, S. K., & Craig, A. (2002). Driver fatigue: electroencephalography and psychological assessment. *Psychophysiology*, *39*(3), 313-321.

Lamble, D., Kauranen, T., Laakso, M., & Summala, H. (1999). Cognitive load and detection thresholds in car following situations: safety implications for using mobile (cellular) telephones while driving. *Accident Analysis & Prevention*, *31*(6), 617–623.

Land, M.F., Lee, D.N., 1994. Where we look when we steer. *Nature, 369*, 742–744.

Land, M.F., Mennie, N., Rusted, J., 1999. The roles of vision and eye movements in the control of activities of daily living. *Perception 28*, 1311–1328.

Lansdown, T.C. (2002). Individual differences during driver secondary task performance: verbal protocol and visual allocation findings. *Accident Analysis and Prevention, 34,* 655-662.

Lee, J. D., Caven, B., Haake, S., & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effect of speech-based e-mail on drivers' attention to the roadway. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *43*(4), 631-640.

Lehtonen, E., Lappi, O., Koirikivi, I., & Summala, H. (2014). Effect of driving experience on anticipatory look-ahead fixations in real curve driving. *Accident Analysis & Prevention*, *70*, 195–208. doi:10.1016/j.aap.2014.04.002

Levin, H. S., Eisenberg, H. M., & Benton, A. L. (Eds.). (1991). Frontal lobe function and dysfunction. Oxford University Press.

Lewis, A., Garcia, R., & Zhaoping, L. (2003). The distribution of visual objects on the retina: connecting eye movements and cone distributions. *Journal of vision*, *3*(11), 21.

Ley, P. (1979). Memory for medical information. *British Journal of Social and Clinical Psychology*, *18*(2), 245-255.

Lezak, M. D. (Ed.). (2004). Neuropsychological assessment. Oxford university press.

Liang, Y., & Lee, J. D. (2010). Combining cognitive and visual distraction: Less than the sum of its parts. *Accident Analysis & Prevention*, *42*(3), 879–888. doi:10.1016/j.aap.2009.05.001

Liang, Y., Reyes, M. L., & Lee, J. D. (2007.). Real-Time Detection of Driver Cognitive Distraction Using Support Vector Machines. *IEEE Transactions on Intelligent Transportation Systems*, *8*(2), 340–350. doi:10.1109/TITS.2007.895298

Lin, C. T., Chen, S. A., Ko, L. W., & Wang, Y. K. (2011, July). EEG-based brain dynamics of driving distraction. In *International Joint Conference on Neural Networks (IJCNN),* 1497-1500.

Lin, C. T., Ko, L. W., & Shen, T. K. (2009). Computational intelligent brain computer interaction and its applications on driving cognition. *Computational Intelligence Magazine, IEEE*, *4*(4), 32-46.

Lin, C.-T., Chen, S.-A., Chiu, T.-T., Lin, H.-Z., & Ko, L.-W. (2011). Spatial and temporal EEG dynamics of dual-task driving performance. *Journal of NeuroEngineering and Rehabilitation*, *8*(1), 11. doi:10.1186/1743-0003-8-11

Linker, E., Moore, M. E., & Galanter, E. (1964). Taste thresholds, detection models, and disparate results. *Journal of experimental psychology*, *67*(1), 59.

Liu, Y. C., Schreiner, C. S., & Dingus, T. A. (1999). *Development of human factors guidelines for advanced traveler information systems (ATIS) and commercial vehicle operations (CVO): Human factors evaluation of the effectiveness of multi-modality displays in advanced traveler information systems* (No. FHWA-RD-96-150,).

Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in cognitive sciences*, *4*(1), 6-14.

Loftus, G. R. (1985). Picture perception: Effects of luminance on available information and information-extraction rate. *Journal of Experimental Psychology: General*, *114*(3), 342.

Loftus, G. R., Duncan, J., & Gehrig, P. (1992). On the time course of perceptual information that results from a brief visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(2), 530.

Low, M. D., Borda, R. P., Frost, J. D., & Kellaway, P. (1966). Surface-negative, slow-potential shift associated with conditioning in man. *Neurology*, *16*(8), 771-771.

Luu P, Flaisch T, Tucker DM (2000) Medial frontal cortex in action monitoring. Journal of Neuroscience 20: 464–469

MacWhinney, B., Keenan, J. M., & Reinke, P. (1982). The role of arousal in memory for conversation. *Memory & Cognition*, *10*(4), 308–317.

Maljkovic, V., & Nakayama, K. (2000). Priming of popout: III. A short-term implicit memory system beneficial for rapid target selection. *Visual Cognition*, *7*(5), 571-595.

Mangun, G. R., & Hillyard, S. A. (1995). Mechanisms and models of selective attention. In M. G. Coles (Ed.), Electrophysiology of the Mind: Event-related Brain Potentials and Cognition (No. 25 ed., pp. p. 40-85). Oxford: Oxford University Press.

Marr, D. (1982). Vision: A computational investigation into the human representation and processing of visual information. New York: Freeman.

Massen, C. (2004). Parallel programming of exogenous and endogenous components in the antisaccade task. Quarterly Journal of Experimental Psychology A, 57, 475–498.

Matthews, R., Legg, S., & Charlton, S. (2003). The effect of cell phone type on drivers' subjective workload during concurrent driving and conversing. Accident Analysis and Prevention, 35, 441-450.

May, J. G., Kennedy, R. S., Williams, M. C., Dunlap, W. P., & Brannan, J. R. (1990). Eye movement indices of mental workload. *Acta psychologica*, *75*(1), 75-89.

McCallum, C. (1969). The contingent negative variation as a cortical sign of attention in man. In *Attention in neurophysiology,* 40-63. Butterworth London.

McCallum, W. C. (1967). The contingent negative variation: an experimental study of a slow potential change in the electroencephalogram of normal subjects and psychiatric patients. *PhD Thesis, University of Bristol, l967*.

McCallum, W. C., & Walter, W. G. (1968). The effects of attention and distraction on the contingent negative variation in normal and neurotic subjects. *Electroencephalography and clinical neurophysiology*, *25*(4), 319-329.

McDonald, W. A., & Hoffman, E. R. (1980). Review of relationships between steering wheel reversal rate and driving task demand. *Human Factors, 22*(6), 733–739.

McKenna, F., & Crick, J. (1997). Developments in hazard perception. *Transportation Research Laboratory* (Report No. 297).

McKenna, F.P., Crick, J.L., 1991. Hazard Perception in Drivers: A Methodology for Testing and Training (Final Report). *Transport Research Laboratory,* Crowthorne, UK.

McPeek, R. M., Skavenski, A. A., & Nakayama, K. (2000). Concurrent processing of saccades in visual search. *Vision Research, 40*, 2499–2516.

Milner, A. D., & Goodale, M. A. (1998). The Visual Brain in Action. *PSYCHE*, *4*, 12.

Milner, A., & Goodale, M. A. (2004). Plans for action. *Behavioral & Brain Sciences*, *27*, 37-40.

Mitchell, J. P., Macrae, C. N., & Gilchrist, I. D. (2002). Working memory and the suppression of reflexive saccades. *Journal of Cognitive Neuroscience*, *14*(1), 95-103.

Miyaji, M., Kawanaka, H., & Oguri, K. (2009). Driver's cognitive distraction detection using physiological features by the adaboost. In *12th International IEEE Conference on Intelligent Transportation Systems, 2009. (ITSC'09),* 1-6.

Moschovakis, A. K., & Highstein, S. M. (1994). The anatomy and physiology of primate neurons that control rapid eye movements. *Annual Review of Neuroscience*, *17*(1), 465–488.

Mosimann, U. P., Felblinger, J., Colloby, S. J., & Muri, R. M. (2004). Verbal instructions and top-down saccade control. *Experimental Brain Research, 159,* 263–267.

Müller, H. J., Heller, D., & Ziegler, J. (1995). Visual search for singleton feature targets within and across feature dimensions. *Perception & Psychophysics*, *57*(1), 1–17.

Munoz, D. P., & Everling, S. (2004). Look away: The anti-saccade task and the voluntary control of eye movement. *Nature Reviews Neuroscience, 5*, 218–228.

Niedermeyer, E. (1999). A concept of consciousness. *The Italian Journal of Neurological Sciences*, *20*(1), 7-15.

Norman, D. A., & Shallice, T. (1986). Attention to action, *1-18*. Springer US.

Norton, D., & Stark, L. (1971). Scanpaths in saccadic eye movements while viewing and recognising patterns. *Vision Research, 11*, 929-942.

O'Regan, J. K. (1992). Solving the" real" mysteries of visual perception: the world as an outside memory. *Canadian Journal of Psychology/Revue canadienne de psychologie*, *46*(3), 461.

Oh, S. H., & Kim, M. S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review*, *11*(2), 275-281.

Ohno-Shosaku, T., Sawada, S., & Kano, M. (2000). Heterosynaptic expression of depolarization-induced suppression of inhibition (DSI) in rat hippocampal cultures. *Neuroscience research*, *36*(1), 67-71.

Olk, B., & Kingstone, A. (2003). Why are antisaccades slower than prosaccades? A novel finding using a new paradigm. *Neuroreport*, *14*, 151–155.

Olsson, S. (2000). Measuring driver visual distraction with a peripheral detection task. *Master thesis, ISRN LIU- KOGVET-D-0031-SE.* Linko ̈ping University, Department of Behavioural Science/Volvo Technology AB.

Onton, J., Delorme, A., & Makeig, S. (2005). Frontal Midline theta dynamics during working memory. *Neuroimage*, *27*, 341-356.

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N‐back working memory paradigm: A meta‐analysis of normative functional neuroimaging studies. *Human brain mapping*, *25*(1), 46-59.

Paré, M., & Wurtz, R. H. (2001). Progression in neuronal processing for saccadic eye movements from parietal cortex area lip to superior colliculus. *Journal of Neurophysiology*, *85*(6), 2545-2562.

Parkhurst, D. J., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision Research, 42,* 107–123.

Patten, C. J. D., Kircher, A., Östlund, J., & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis & Prevention*, *36*(3), 341–350. doi:10.1016/S0001-4575(03)00014-9

Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science*, *12*(4), 287-292.

Pierrot-Deseilligny, C. H., Rivaud, S., Gaymard, B., & Agid, Y. (1991). Cortical control of reflexive visually-guided saccades. *Brain*, *114*(3), 1473-1485.

Polich, J., Ellerson, P. C., & Cohen, J. (1996). P300, stimulus intensity, modality, and probability. *International Journal of Psychophysiology*, *23*(1), 55-62.

Pratt, J. (1998). Visual fixation offsets affect both the initiation and the kinematic features of saccades. *Experimental Brain Research, 118*, 135–138.

Quimby, A. R., & Watts, G. R. (1981). Human factors and driving performance. *Transportation Research Board* (Report No. LR 1004 Monograph).

Quimby, A. R., Maycock, G., Carter, I. D., Dixon, R., & Wall, J. G. (1986). *Perceptual abilities of accident involved drivers* (No. RR 27).

Raghavachari, S., Kahana, M. J., Rizzuto, D. S., Caplan, J. B., Kirschen, M. P., Bourgeois, B., & Lisman, J. E. (2001). Gating of human theta oscillations by a working memory task. *The journal of Neuroscience*, *21*(9), 3175-3183.

Rakauskas, M. E., Gugerty, L. J., & Ward, N. J. (2004). Effects of naturalistic cell phone conversations on driving performance. *Journal of safety research*, *35*(4), 453-464.

Rakauskas, M. E., Ward, N. J., Bernat, E., Cadwallader, M., Patrick, C., & de Waard, D. (2005). Psychophysiological measures of driver distraction and workload while intoxicated. In *3rd International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.

Rantanen, E. M., & Goldberg, J. H. (1999). The effect of mental workload on the visual field size and shape. *Ergonomics*, *42*(6), 816-834.

Ray, W. J., & Cole, H. W. (1985). EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science*, *228*(4700), 750-752.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372.

Rayner, K., Li, X., Williams, C. C., Cave, K. R., & Well, A. D. (2007). Eye movements during information processing tasks: Individual differences and cultural effects. *Vision research*, *47*(21), 2714-2726.

Recarte, M. A., & Nunes, L. (2002). Mental load and loss of control over speed in real driving.: Towards a theory of attentional speed control. *Transportation Research Part F: Psychology and Behaviour*, *5*(2), 111–122.

Recarte, M. A., & Nunes, L. M. (2000). Effects of verbal and spatial-imagery task on eye fixations while driving. *Journal of Experimental Psychology: Applied,* 6, 31-43.

Recarte, M. A., & Nunes, L. M. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied*, *9*(2), 119–137. doi:10.1037/1076-898X.9.2.119

Recarte, M. Á., Pérez, E., Conchillo, Á., & Nunes, L. M. (2008). Mental workload and visual impairment: Differences between pupil, blink, and subjective rating. *The Spanish journal of psychology*, *11*(02), 374-385.

Redelmeier, D. A., & Tibshirani, R. J. (1997). Association between cellular-telephone calls and motor vehicle collisions. *New England Journal of Medicine*, *336*(7), 453–458.

Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. Transportation Research Record, 2138, 13–19. doi:10.3141/2138-03.

Reuter-Lorenz, P. A., Oonk, H. M., Barnes, L. L., & Hughes, H. C. (1995). Effects of warning signals and fixation point offsets on the latencies of pro-versus antisaccades: implications for an interpretation of the gap effect. *Experimental Brain Research*, *103*(2), 287-293.

Reuter-Lorenz, P. A., Oonk, H. M., Barnes, L. L., & Hughes, H. C. (1995). Effects of warning signals and fixation point offsets on the latencies of pro- versus antisaccades: Implications for an interpretation of the gap effect*.* *Experimental Brain Research, 103,* 287–293.

Robert, G., & Hockey, J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological psychology*, *45*(1), 73-93.

Ross, M., & Sicoly, F. (1979). Egocentric biases in availability and attribution. *Journal of personality and social psychology*, *37*(3), 322.

Rousseau, J. C., Bostem, F., & Dongier, M. (1968). Studies on CNV: interest of recording its progressive construction during summation. *Electroencephalography and clinical neurophysiology*, *24*(1), 95-95.

Ryu, K., & Myung, R. (2005). Evaluation of mental workload with a combined measure based on physiological indices during a dual task of tracking and mental arithmetic. *International Journal of Industrial Ergonomics*, *35*(11), 991–1009. doi:10.1016/j.ergon.2005.04.005

Sagberg, F., & Bjørnskau, T. (2006). Hazard perception and driving experience among novice drivers. *Accident Analysis & Prevention*, *38*(2), 407–414. doi:10.1016/j.aap.2005.10.014

Savage, S. W., Potter, D. D., & Tatler, B. W. (2013). Does preoccupation impair hazard perception? A simultaneous EEG and Eye Tracking study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *17*, 52–62. doi:10.1016/j.trf.2012.10.002

Schall JD (1997) Visuomotor areas of the frontal lobe. In: *Cerebral Cortex, vol. 4*, (Eds.) Rockland, A. Peters, and J. Kaas. New York: Plenum, 527-638.

Schall, J. D. (1995). Neural basis of saccade target selection. *Reviews in the Neurosciences, 6,* 63–85.

Schier, M. A. (2000). Changes in EEG Alpha Power During Simulated Driving: a Demonstration. *International Journal of Psychophysiolog, 37*, 155-162.

Schlag-Rey, M., Amador, N., Sanchez, H., & Schlag, J. (1997). Antisaccade performance predicted by neuronal activity in the supplementary eye field. *Nature*, *390*(6658), 398-401.

Schmidt, D., Abel, L. A., DellOsso, L. F., & Daroff, R. B. (1979). Saccadic velocity characteristics, Intrinsic variability and fatigue. *Aviation, Space, and Environmental Medicine*, *50*(4), 393–395.

Serafin, C., Wen, C., Paelke, G., Green, P., 1993. Car phone usability: a human factors laboratory test. In: Proceedings of the *Human Factors and Ergonomics Society, 37th Annual Meeting,* 220–224.

Shallice, T., & Burgess, P. W. (1993). Supervisory control of action and thought selection. In: Baddeley, A., & Weiskrantz, L. (eEs.) *Attention: Selection, Awareness and Control: A Tribute to Donald Broadbent.*, 171 - 187. Clarendon Press: Oxford.

Shinoda, H., Hayhoe, M. M., & Shrivastava, A. (2001). What controls attention in natural environments? *Vision Research, 41,* 3535–3545.

Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision, 14,* 59–75.

Simonin, J., Kieffer, S., & Carbonell, N. (2005). Effects of display layout on gaze activity during visual search. In: M.F. Costabile and F. Paternò (Eds.), *INTERACT 2005*, 1054-1057.

Siveraag, E. J., & Stern, J. A. (2000). Ocular measures of fatigue and cognitive factors. In R. W. Backs & W. Boucsein (Eds.), *Engineering psychophysiology: Issues and applications.* Mahwah, NJ: Erlbaum, 269-287.

Smit, A. C., Van Gisbergen, J. A. M., & Cools, A. R. (1987). A parametric analysis of human saccades in different experimental paradigms. *Vision research*, *27*(10), 1745-1762.

Smyrnis N., Evdokimidis, I., Stefanis, N., Constantinidis, T., Avramopoulos, D., Theleritis, C., Paximadis, C., Efstratiadis, C., Kastrinakis, G., & Stefanis, C.N. (2002). The antisaccade task in a sample of 2,006 young males. II. Effects of task parameters. *Experimental Brain Research, 147*, 53–63

Sodhi, M., Reimer, B., Llamazares, I., 2002. Glance analysis of driver eye movements to evaluate distraction. *Behavior Research Methods Instruments and Computers, 34* (4), 529–538.

Solman, G. J., Cheyne, J. A., & Smilek, D. (2011). Memory load affects visual search processes without influencing search efficiency. *Vision research*, *51*(10), 1185-1191.

Stafford, L., & Daly, J.A. (1984). Conversational memory: The effects of recall mode and memory expectancies on remembrances of natural conversations. *Human Communication Research, 10*, 379-402.

Stafford, L., Burggraf, C.S., & Sharkey, W.F. (1987). Conversational memory: The effects of time, recall mode, and memory expectancies on remembrances of natural conversations. *Human Communication Research, 14*, 203-229.

Stern, J.A., Boyer, D., Schroeder, D., 1994. Blink rate: a possible measure of fatigue. *Human Factors 36*, 285–297.

Sternberg, S. (1969). Memory scanning: Mental processes revealed by reaction-time experiments. *American Scientist, 57,* 421-457.

Stevens, J. R., & Livermore, A. (1982). Telemetered EEG in schizophrenia: spectral analysis during abnormal behaviour episodes. *Journal of Neurology, Neurosurgery & Psychiatry*, *45*(5), 385-395.

Strayer, D. L. & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors, 46,* 640–649.

Strayer, D. L., & Drews, F. A. (2007). Cell-phone–induced driver distraction. *Current Directions in Psychological Science*, *16*(3), 128-131.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological science*, *12*(6), 462-466.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of experimental psychology: Applied*, *9*(1), 23.

Strayer, D. L., Drews, F. A., Albert, R. W., & Johnston, W. A. (2001). Cell phone induced perceptual impairments during simulated driving. *Driving Assessment*, 14-19.

Stuphorn, V., Taylor, T. L., & Schall, J. D. (2000). Performance monitoring by the supplementary eye field. *Nature, 408,* 857–860.

Stutts, J.C., Reinfurt, D.W., Staplin, L., & Rodgman, E.A. (2001). The role of driver distraction in traffic crashes. *Washington, DC: AAA Foundation for Traffic Safety*.

Stuyven, E., Van der Goten, K., Vandierendonck, A., Claeys, K., & Crevits, L. (2000). The effect of cognitive load on saccadic eye movements. *Acta Psychologica, 104*, 69–85.

Tanner Jr, W. P., Swets, J. A., & Green, D. M. (1956). Some general properties of the hearing mechanism. *University of Michigan, Electronic Defence Group*.

Tatler, B. W. (2007). The central fixation bias in scene viewing: Selecting an optimal viewing position independently of motor biases and image feature distributions. *Journal of Vision, 7*(14), 1–17, Tatler, B. W., & Hutton, S. B. (2007). Trial by trial effects in the antisaccade task. *Experimental Brain Research, 179*, 387–396.

Tatler, B. W., & Vincent, B. T. (2009). The prominence of behavioural biases in eye guidance. *Visual Cognition, 17,* 1029–1054.

Tatler, B. W., Baddeley, R. J., & Gilchrist, I. D. (2005). Visual correlates of fixation selection: Effects of scale and time. *Vision Research, 45,* 643–659.

Tatler, B. W., Baddeley, R. J., & Vincent, B. T. (2006). The long and the short of it: Spatial statistics at fixation vary with saccade amplitude and task. *Vision Research, 46,* 1857–1862.

Tatler, B. W., Baddeley, R. J., & Vincent, B. T. (2006). The long and the short of it: Spatial statistics at fixation vary with saccade amplitude and task. *Vision Research, 46,* 1857–1862.

Tecce, J. J., & Scheff, N. M. (1969). Attention reduction and suppressed direct-current potentials in the human brain. *Science*, *164*(3877), 331-333.

Teplan, M. (2002). Fundamentals of EEG measurement. *Measurement Science Review, 2*(2), 1–11.

Tesche C, Karhu J (2000) Theta oscillations index human hippocampal activation during a working memory task. *Proceedings of the National Academy of Sciences, USA 97*, 919 –924.

Thomas, M.I., & Russo, M.B. (2007). Neurocognitive monitors: toward the prevention of cognitive performance decrements and catastrophic failures in the operational environment. *Aviation, Space & Environmental Medicine 78*, 144–152.

Tien, A. Y., Ross, D. E., Pearlson, G., & Strauss, M. E. (1996). Eye movements and psychopathology in schizophrenia and bipolar disorder. *Journal of Nervous and Mental Disease, 184,* 331–338.

Tijerina, L., Parmer, E., & Goodman, M., (1998). Driver workload assessment of route guidance system destination entry while driving: a test track study. In: *5th ITS World Congress,* Seoul, Korea.

Törnros, J. E. B., & Bolling, A. K. (2005). Mobile phone use – Effects of handheld and handsfree phones on driving performance. *Accident Analysis and Prevention, 37*, 902–909.

Treffner, P. J., & Barrett, R. (2004). Hands-free mobile phone speech while driving degrades coordination and control. *Transport Research, Part F, 7,* 229–246.

Treisman, A. (1988). Features and objects: The 14th Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology,* 4OA, 201-237.

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97-136.

Treisman, A., & Sata, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception* & *Performance,* 16, 459-478.

Trick, L. M., Enns, J. T., Mills, J., & Vavrik, J. (2004). Paying attention behind the wheel: a framework for studying the role of attention in driving. *Theoretical Issues in Ergonomics Science, 5*(5), 385 - 424.

Tulving, E., Kapur, S., Craik, F. I., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: positron emission tomography findings. *Proceedings of the National Academy of Sciences*, *91*(6), 2016–2020.

Underwood, G., Chapman, P., Bowden, K., & Crundall, D. (2002). Visual search while driving: skill and awareness during inspection of the scene. *Transportation Research Part F: Traffic Psychology and Behaviour, 5*(2), 87-97.

Underwood, G., Crundall, D., & Chapman, P. (2002a). Selective searching while driving: the role of experience in hazard detection and general surveillance. *Ergonomics, 45*(1), 1-12.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working Memory Capacity and the Antisaccade Task: Individual Differences in Voluntary Saccade Control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(6), 1302–1321. doi:10.1037/0278-7393.30.6.1302

van Boxtel, G. J., & Böcker, K. B. (2004). Cortical measures of anticipation. *Journal of Psychophysiology*, *18*(2-3), 61. doi:10.1027/0269-8803.18.2–3.61

Van Diepen, P. M., De Graef, P., & d'Ydewalle, G. (1995). Chronometry of foveal information extraction during scene perception. *Studies in visual information processing*, *6*, 349-362.

Van Wert, M. J., Horowitz, T. S., & Wolfe, J. M. (2009). Even in correctable search, some types of rare targets are frequently missed. *Attention, Perception, & Psychophysics*, *71*(3), 541-553.

Vaughan, H. G., Costa, L. D., & Ritter, W. (1968). Topography of the human motor potential. *Electroencephalography and clinical neurophysiology*, *25*(1), 1-10.

Velichkovsky, B. M., Rothert, A., Kopf, M., Dornhoefer, S. M., & Joos, M. (2002). Towards an express-diagnostics for level of processing and hazard perception. *Transportation Research, Part F, 5,* 145–156.

Veltman, J. A., & Gaillard, A. W. K. (1996). Physiological indices of workload in a simulated flight task. *Biological Psychology, 42*, 323–342.

Victor, T. W., Harbluk, J. L., & Engström, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(2), 167-190.

Vidal, F., Hasbroucq, T., Grapperon, J., & Bonnet, M. (2000). Is the 'error negativity' specific of errors? *Biological Psychology, 51*, 109–128.

Viviani, P., Berthoz, A., & Tracey, D. (1977). The curvature of oblique saccades. *Vision research*, *17*(5), 661-664.

von Stein, A., Rappelsberger, P., Sarnthein, J., Petsche, H. (1999). Synchronization between temporal and parietal cortex during multimodal object processing in man. *Cerebral Cortex, 9,* 137– 150.

Walker, R., Walker, D. G., Husain, M., & Kennard, C. (2000). Control of voluntary and reflexive saccades. *Experimental Brain Research*, *130*(4), 540–544. doi:10.1007/s002219900285

Walter, W. G. (1965). Brain responses to semantic stimuli. *Journal of psychosomatic research*, *9*(1), 51-61.

Walter, W. G. (1968). The contingent negative variation: an electro-cortical sign of sensori-motor reflex association in man. *Progress in brain research*, *22*, 364-377.

Walter, W. G., Cooper, R., Crow, H. J., McCallum, W. C., Warren, W. J., Aldridge, V. J., ... & Kamp, A. (1967). Contingent negative variation and evoked responses recorded by radio-telemetry in free-ranging subjects. *Electroencephalography and clinical neurophysiology*, *23*(3), 197-206.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C., & Winter, A.L. (1964). Contingent negative variation: An electric sign of sensorimotor association and expectancy in the human brain. *Nature*, *203*, 380–384.

Wester, A. E., Böcker, K. B. E., Volkerts, E. R., Verster, J. C., & Kenemans, J. L. (2008). Event-related potentials and secondary task performance during simulated driving. *Accident Analysis & Prevention*, *40*(1), 1–7. doi:10.1016/j.aap.2007.02.014

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449-455.

Wickens, C.D., 2002. Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science 3* (2), 159–177.

Wickens, C.D., Isreal, J. & Donchin, E. (1977). The event-related cortical potential as an index of task workload. *Proceedings of the Twenty-First Annual Meeting of the Human Factors Society, San Francisco*.

Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics*, *1*(9), 315-318.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review, 1*, 202–238.

Wolfe, J. M., & Gancarz, G. (1996). Guided Search 3.0: A model of visual search catches up with Jay Enoch 40 years later. In V. Lakshminarayanan (Ed.), *Basic and clinical applications of vision science,* 189-192. Berkeley, CA: Kluwer Academic Publishers.

Wolfe, J. M., & Van Wert, M. J. (2010). Varying target prevalence reveals two dissociable decision criteria in visual search. *Current Biology*, *20*(2), 121-124.

Wolfe, J. M., Cave, K. R. & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search**,** *Journal of Experimental Psychology, Human Perception and Performance*, 15, 419-433

Wolfgang, K. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews, 29*(2), 169–195.

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review, 11*, 269–274.

Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science, 12*, 219–224.

Yarbus, A. L. (1967). Eye movements during perception of complex objects. In *Eye movements and vision* , 171-211. Springer US.

Young, K. & Regan, M. (2007). Driver distraction: A review of the literature. In: I.J. Faulks, M. Regan, M. Stevenson, J. Brown, A. Porter & J.D. Irwin (Eds.). *Distracted driving,* 379-405. Sydney, NSW: Australasian College of Road Safety, Young, K., Lee, J. D., & Regan, M. A. (Eds.). (2008). Driver distraction: Theory, effects, and mitigation. CRC Press.

Zelinsky, G. J., & Sheinberg, D. L. (1997). Eye movements during parallel–serial visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(1), 244.

Zhang, Y., Owechko, Y., & Zhang, J. (2004, October). Driver cognitive workload estimation: A data-driven perspective. In *Intelligent Transportation Systems, 2004. Proceedings. The 7th International IEEE Conference on* (pp. 642-647). IEEE.

Zils, E., Sprenger, A., & Heide, W. (2005). Differential effects of sleep deprivation on saccadic eye movements. *SLEEP*, *28*(9), 1109-1115.

Appendix

Chapter II & Chapter III

Riddles:

1) What English word has three consecutive double letters?- Bookkeeper
2) What's black when you get it, red when you use it, and white when you're all through with it? – Charcoal
3) What always runs but never walks, often murmurs, never talks, has a bed but never sleeps, has a mouth but never eats? – a river
4) The person who makes it, sells it. The person who buys it never uses it and the person who user s it doesn't know they are. What is it? – A coffin
5) What has to be broken before it can be used? – An egg
6) What has only two words, but thousands of letters? – Post office
7) The more you take, the more you leave behind. What are they? – footsteps
8) When one does not know what it is, then it is something; but when one knows what it is, then it is nothing. – a riddle
9) What is it that everybody does at the same time? – grow older
10) A girl who was just learning to drive went down a one-way street in the wrong direction, but didn't break the law. How come? – She was walking
11) A prisoner is told "If you tell a lie we will hang you; if you tell the truth we will shoot you." What can he say to save himself? - You will hang me. If they hang him, then the statement was true and they could only hang him for telling a lie. If they shoot him, then it makes the statement a lie and they were only to shoot him for telling the truth. An alternate solution is to say, "You will not shoot me," leading to the same quandary for the killers.
12) How far can a dog run into the forest? Halfway – afterwards he’s running out
13) Name three consecutive days without using the words Wednesday, Friday, or Sunday. – Yesterday, today. Tomorrow
14) If you were to spell out the numbers, how far would you have to go before encountering the letter 'A'? one thousand (or one hundred AND one)

15) A clock loses exactly ten minutes every hour. If the clock is set correctly at noon, what is the correct time when the clock reads 3:00pm? A clock loses exactly ten minutes every hour. If the clock is set correctly at noon, what is the correct time when the clock reads 3:00pm?
16) Two days ago Lilly was 7 years old. Next year she will turn 10. How can this be? - Her birthday is on December 31st. Today is January 1st so she was 7 two days ago, now she's 8. She will turn 9 this year and next year she'll turn 10.
17) What is round as a dishpan and no matter the size, all the water in the ocean can't fill it up? – A sieve
18) What is is that you will break every time you name it? - Silence
19) What grows in winter, dies in summer, and grows roots upward? - An icicle
20) What turns everything around, but does not move? - A Mirror
21) What has a tongue, cannot walk, but gets around a lot? – A Shoe
22) What runs around a house but doesn't move? - A fence
23) What gets whiter the dirtier it gets? – Chalkboard
24) What can you catch but not throw? A Cold
25) What sits in a corner while traveling all around the world? A stamp
26) What needs an answer, but doesn't ask a question? A telephone
27) What travels around the world all year without using a single drop of petrol? – The moon
28) What kind of running means walking? Running out of petrol
29) A man drove 200 miles without noticing that he had a flat tire. How can this be? His spare tyre was flat

Easy Questions:

1) What is the capital of France? – Paris
2) What is eight divided by four? – 2
3) How many wheels are there on a car? - 4
4) How many wheels are there on a motorbike? -2
5) How many letters are there in the word sky? 3
6) What is the capital of England? - London
7) What is ten plus five? - 15
8) Who is the current prime minister of England? – Cameron
9) Who is the current president of the United States?
10) What is the Capital of Scotland?

11) What is capital of Germany?
12) What is the largest number or a regular die?
13) What language is spoken in Poland?
14) Where can you find the Eiffel Tower?
15) What is four multiplied by five?
16) What is twenty minus ten?
17) At what temperature does water freeze?
18) In what town can you find the Tower Bridge?
19) Which University do you study at?
20) What is half of twenty?
21) At what temperature does water boil and turn into steam?
22) How many letters are there in the word “Door”?
23) Where can you find the white house? Washington DC
24) What is the opposite of white? black
25) Whats your favourite colour? .
26) How many legs does a cat have?
27) How many horns does a bull have? – two
28) What do you study?
29) What is the chemical formula for Oxygen
30) What is 100 – 50 ? 50
31) What is the opposite of happy?
32) What is the typical colour for a fire engine?
33) What is the highest mountain in the world? – Mt Everest
34) Linda reads ten pages of her book every day. How many pages does she read in a week - 70
35) What is 10 + 10
36) What is the capital of Scotland?
37) How many sides are there on a triangle
38) What is 100 – 10
39) What is 200 – 100
40) What is 10 times 10

Chapter IV

Wordlists

1) soot, joker, captain, fly, story, stove, rock, corn, bread, sofa, star, peel, uncle, hospital, grass
2) desk, ranger, bird, shoe, stove, mountain, glasses, towel, cloud, lamb, boat, gun pencil, church, fish
3) drum ,curtain, bell, coffee, school, partent, moon, garden, hat, farmer,nose,turkey, colour,house, river
4) doll, mirror, nail, sailor, heart, dessert, face, letter, bed, machine, milk, helmet, music, horse, road
5) dish, jester, hill, coat, tool , forest, water, ladder, girl, foot, shield, pie, insect, ball, car
6) violin, tree, scarf, ham, suitcase, cousin, earth, knife, stair, dog, banana, radio hunter, bucket, field
7) orange, armchair, toad, cork, bus, chin, beach, soap, hotel, donkey, spider, bathroom, casserole, soldier, lock
8) book, flower, train, rug, meadow, harp, salt, finger, apple, chimney, button, log key, rattle, gold
9) toffee, sand, pony, plate, heart, jail, envelope, silk, dart screw, wood, stool bread, street, head
10) barn, window, hand, hole, balloon, mouse, crayon, fountain, hot, stranger, stocking, teacher, nest, children, rose

Easy Questions

1) What is the Queens name? Elizabeth
2) How many sides does a square have? Four
3) What city are you in? Dundee
4) If you have three apples and four bananas, how many items of fruit do you have in total? Seven
5) What is the capital city of Scotland? Edinburgh
6) What is the name of the American president? Barrack Obama
7) What date does Christmas fall on each year? 25th of December
8) What do people blow out on their birthdays? candles
9) What is five multiplied by ten? fifty
10) What is one hundred minus twenty five? 75

Driving Questionnaire

Before

Participant number	
Sex	
Age	

How much driving experience do you have?

How long and how regularly do you drive each week?

After

How much more difficult on a scale of 1-10 did you find the hazard perception task whilst being preoccupied?

How difficult on a scale of 1-10 did you find the distractor task whilst trying to complete the hazard perception task?

General Questions

How did you find the task overall?

Do you think the task was a good test of driver preoccupation?

Digit Span Task

3 DIGIT SPAN

Discontinue after failure on BOTH TRIALS of any item.
Administer BOTH TRIALS of each item, even if subject passes first trial.

DIGITS FORWARD		Pass-Fail	Score 2, 1, or 0
1	5–8–2		
	6–9–4		
2	6–4–3–9		
	7–2–8–6		
3	4–2–7–3–1		
	7–5–8–3–6		
4	6–1–9–4–7–3		
	3–9–2–4–8–7		
5	5–9–1–7–4–2–8		
	4–1–7–9–3–8–6		
6	5–8–1–9–2–6–4–7		
	3–8–2–9–5–1–7–4		
7	2–7–5–8–6–2–5–8–4		
	7–1–3–9–4–2–5–6–8		
	Total Forward		Max = 14

DIGITS BACKWARD*		Pass-Fail	Score 2, 1, or 0
1	2–4		
	5–8		
2	6–2–9		
	4–1–5		
3	3–2–7–9		
	4–9–6–8		
4	1–5–2–8–6		
	6–1–8–4–3		
5	5–3–9–4–1–8		
	7–2–4–8–5–6		
6	8–1–2–9–3–6–5		
	4–7–3–9–1–2–8		
7	9–4–3–7–6–2–5–8		
	7–2–8–1–9–6–5–3		
	Total Backward		Max = 14

Forward	+	Backward	=	Total
				Max = 28

* Administer DIGITS BACKWARD even if subject scores 0 on DIGITS FORWARD.

Chapter V

Wordlist

WL 1: soot, joker, captain, fly, story, stove, rock, corn, bread, sofa

WL 2: star, peel, uncle, hospital, grow, desk, ranger, bird, shoe, fish

WL 3: stove, mountain, glasses, towel, cloud, lamb, boat, gun, pencil, church

WL 4: drum ,curtain, bell, coffee, school, parent, moon, garden, hat, farmer

WL 5: nose,turkey, colour, house, river, doll, mirror, nail, sailor, heart,

WL 6: dessert, face, letter, bed, machine, milk, helmet, music, horse, road

WL 7: forest, water, ladder, girl, foot, shield, pie, insect, ball, car

WL 8: dish, jester, hill, coat, tool, violin, tree, scarf, ham, suitcase,

WL 9: cousin, earth, knife, stair, dog, banana, radio hunter, bucket, field

WL 10: orange, armchair, toad, cork, bus, chin, beach, soap, hotel, donkey,

WL 11: spider, bathroom, casserole, soldier, lock, book, flower, train, rug, meadow

WL 12: harp, salt, finger, apple, chimney, button, log, key, rattle, gold

WL 13: toffee, sand, pony, plate, heart, jail, envelope, silk, dart screw

WL 14: wood, stool bread, street, head, barn, window, hand, hole, balloon,

WL 15: mouse, crayon, fountain, hot, stranger, stocking, teacher, nest, children, rose

Easy Questions:

Q1: What is the capital city of Scotland?

Q2: What is the capital city of England?

Q3: What city are you in?

Q4: What is five multiplied by ten?

Q5: What is one hundred minus twenty five?

Q6: What do people blow out on their birthdays?

Q7: How many sides does a square have?

Q8: What is the capital city of France?

Q9: What is half of one hundred?

Q10: How many sides does a triangle have?

Q11: What is four multiplied by five

Q12 What is three times ten?

Q13: What is the capital city of Germany?

Q14: At what temperature does water begin to boil?

Q15: At what temperature does water begin to freeze?

Hazard Stills from Experiments 3 & 4

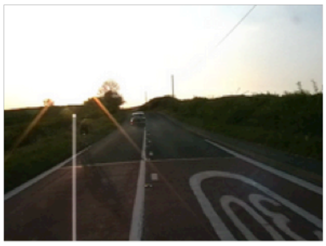
Car Merging into lane

Car stopped on lane

Pedestrian crossing

Car cutting into lane

Car approaching in lane



Cyclist on Roadside

Pedestrian on Roadside

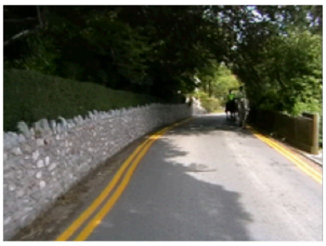
Bus stopped in lane

Bus stopped in lane

Car cutting into lane

Pedestrian on Roadside

Car approaching in lane



Horses on Roadside

Cyclist in lane

Pedestrian crossing

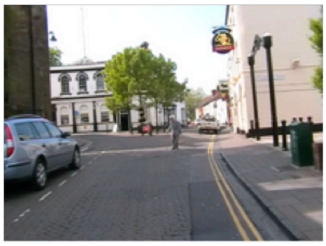
Pedestrian Crossing

Car stopped on lane

Car pulling out

Tractor in lane

Pedestrian on Roadside



Pedestrian Crossing

Car approaching in lane

Car cutting into Lane

Car pulling out

Motorcycle pulling out

Car parked in lane

Van stopping in lane

Pedestrian on Roadside

Car stopped on lane

Pedestrian crossing